Soil profile properties affecting grapevine root growth, vine vigour and fruit yield

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Declaration of Originality

"This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of the my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright."

Samuel Rees

STATEMENT OF AUTHORITY OF ACCESS

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Abstract

Tasmania provides one of the most diverse ranges of soil types for viticultural production in the world ranging from alkaline heavy clay soils (Vertosols) to acidic sandy soils (Podosols). Wide variations in yield and quality have hindered the development of the industry in Tasmania, the extent to which these variations are influenced by soil factors is largely unknown. This diverse Tasmanian environment provides an ideal location for the investigation of soil - root interactions and their relationship to vine productivity.
Investigations of grapevine root distribution were undertaken within a range of soil types across three vineyards located in Tasmania. Soil trenches were excavated to expose soil profiles and vine root distribution with root size frequency and soil penetration resistance recorded across the soil face. The soil profile was described for physical properties and all horizons were sampled for chemical analysis. Vine growth parameters such as pruning weight and fruit yield were also measured over several seasons.
The percentage distribution of roots vertically through the soil profiles was very similar regardless of soil type. Highest root abundance occurred at 10 – 30 cm depth for all but one of the studied profiles. Root numbers declined with depth below 30 cm, with most profiles having 80 % of total root growth within a depth of 0 – 60 cm. Limited root growth was observed in the upper 0 – 10 cm of the soil profile with many soil profiles having no roots recorded in the upper 0 – 5 cm. This was despite these layers having the highest soil fertility and lowest soil penetration resistance. Even though the majority of the roots were in the upper 60 cm, deep profile features such as unconsolidated layers or access to deep water tables were observed to greatly enhance vine growth.
While the vertical distribution of roots was similar between all profiles, the horizontal distribution of roots varied considerably between soil profiles. Soil structure and soil strength both had a primary influence on root growth. Roots consistently grew between the structural units of the soil at all profiles, regardless of the soil type or the type of soil structure expressed. This was particularly evident in horizons where the structural units were coarse which resulted in root growth being confined to distinct regions of weakness such as vertical structural cracks, sand in-fills and/or old (dead) roots and root channels. Therefore the extent of these favourable situations determined how widely the roots were

distributed across the soil profile face. Root distribution within many subsoils was also locally constrained by soil chemical attributes including low soil pH, high ESP and/or shallow saline watertables.

While consistent relationships were observed between soil properties and root distribution, there was no clear relationship between vine growth and the size of the root system. Most importantly, greater root numbers did not necessarily produce higher vine growth nor did low root numbers always result in lower vine growth. This signifies that the efficiency and function of the roots is more important than total root abundance *per se*. Soils with differing properties will have different 'optimum' root numbers and distributions for productive vine growth. Consequently soil properties need to be considered in order to understand the influence of root distribution on vine performance.

Differences in vine vigour (pruning weight) and fruit yield were associated with differing soil properties. Low grapevine vigour and fruit yield was associated with thin topsoils (< 20 cm), acidic subsoils (pH < 4.5, 1:5 water) and shallow (< 40 cm) and saline >5 dS/m) watertables. In contrast, high grapevine vigour and fruit yield was associated with deep rooting conditions, either from well-structured, friable colluvial soils or soils with over-thickened topsoil (> 40 cm) caused by clearing and burning during vineyard establishment. No clear relationships were observed between whole soil chemical fertility and vine growth. This suggests that the distribution of roots and their access and supply of nutrients and moisture are a more significant controlling factor.

Root distribution with depth was relatively uniform across the study. However horizontal root distribution was variable across many profiles which is expected to impact on vine management. The soils showed that the variation in vine growth and yield were closely related to variation in soil structural properties and their effect on root efficiency and function. Root distribution generally followed preferential water movement pathways, highlighting the importance of appropriate water management. Optimal root number for vine productivity is soil type dependent and needs specific soil management strategies to optimise yield – quality factors. Therefore understanding variability of soil in both the soil profile and the landscape is important for appropriate management of the variability in vineyard production.

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1. Introduction

Viticulture in Tasmania is a small, but steadily increasing, industry. Bearing area has increased from approximately 200 hectares in 1991 to over 1800 ha in 2014. Much of the production occurs on a small (< 2 ha) to moderate (5 – 10 ha) sized vineyards, with only a few larger producers (50 – 100 ha). Within the current global climate, Tasmania is well placed for future viticultural investment due to predictions of only moderate temperature rises. If the viticultural industry is to expand effectively, then knowledge of suitable sites for vineyard establishment specific to Tasmania is needed.

The distribution of geology and soil throughout Tasmania is highly varied in which changes can occur across small distances. Very diverse soil types are therefore often found within close proximity to each other. Understanding the role that these different soils and their properties have on influencing vines is therefore a critical part of the site selection process. While there are many references relating to the discussion of soil properties for Australian viticultural production (e.g. Northcote, 1988; White, 2003) there is an increasing awareness of how variable production can be within vineyards (e.g. Bramley and Lamb, 2003; Bramley and Hamilton, 2004). There is also an increased use of remote sensing techniques to assist in the determination of such variability (Bramley, 2003; Bramley and Hamilton, 2007). Understanding the underlying causes of this variability is seen as both complementary and necessary before any changes in management can be implemented.

Much of the current viticultural research has concentrated on cultivar, rootstocks or canopy management techniques (e.g. May, 1994; Walker et al, 1997; Conradie, 1983; Walker et al 2000). However, of all the factors influencing wine production, knowledge of the distribution and function of the vine root system is one of the least understood (Cass, 2004).

If the Tasmanian viticultural industry is to expand effectively then knowledge of what makes a suitable site is extremely important. To do this successfully, understanding of how vine roots grow within different soils is required. This will be particularly important for larger investments, where many diverse soils types may be utilised.

This study aims to investigate how soil properties influence vine root growth and root distribution and their effect on above ground growth. Understanding root distribution was seen as a key objective of the study as this is considered necessary to guide future research into water use efficiency and appropriate nutrient sampling and subsequent management. There was not the capacity to examine all of the different regions or soil types currently used for viticulture in Tasmania. Instead, the focus was mainly on soils formed either from Jurassic dolerite or Tertiary sediments. These two parent materials were chosen due to the dolerite soils covering one third of Tasmania and being highly prized for viticultural production and the Tertiary sediments having one of the largest utilisation of vineyards in Tasmania. Other sites investigated included basalt and doleritic colluvium overlying Permian sedimentary strata.

The study will consist of a series of case studies where the following research questions will be investigated:

1. What influence does soil parent material have on soil properties?
2. How do soil properties influence root distribution and/or vine growth?
3. What management techniques might be used to overcome the inherent constraints to vine growth in the soils studied?

Question 1 will be answered by comparing the chemical and physical properties of the studied soils and comparing how differing parent materials have influenced soil composition.

Question 2 will build on answers of Question 1, and will investigate which soil properties identified influence root distribution and vine vigour and fruit yield of grapevines.

Question 3 will synthesise the concepts learnt from the previous questions and discuss potential techniques for management of the respective soils for vineyard production.

2. The role of soil on vine performance (Literature Review)

Tasmanian geology, soil diversity and Terroir

Tasmania is characterised by a diverse landscape. While only being a relatively small island (c. 68,500 km^2) it contains rocks representing every geological period (Manchester, 2010). This has created a wide variety of parent rocks and derived parent materials from which many diverse soil types have formed in close proximity to each other. Seven main viticultural regions exist in Tasmania; Derwent Valley, Coal River Valley, Huon, East Coast, Tamar Valley, North-East, North-West with each having a high diversity of lithology and parent materials (Figure 1). Tasmania can be described as a natural laboratory, providing an ideal situation for investigating how different soils influence many facets of agricultural and horticultural production in a cool temperate climate.

Research and mapping soils in Tasmania has occurred in three main phases. The mid 1950's saw the first official soil mapping programme with the CSIRO Division of Soils (Adelaide) undertaking a series of reconnaissance soil surveys at a scale of 1:63,360. This mapping programme continued until 1964 by which time ten map sheets were produced covering c.1,075,000 ha of the state (Cowie, 1958; Dimmock, 1957; Dimmock, 1961; Dimmock and Nicolls, 1964; Loveday, 1955a; Loveday 1955b; Loveday and Dimmock, 1958; Loveday and Farquhar, 1958; Nicolls, 1958; Nicolls, 1959). In recent years these map sheets have been revised to reflect the Australian Soil Classification system (Isbell, 1996) and republished at 1:100,000. However, no new field observations or changes to soil boundaries were made during these revisions.

After the CSIRO programme ended in 1964, a hiatus in further broad scale soil investigations occurred. It was not until the early 1990's when funding from the National

Landcare Program (previously the National Soil Conservation Program) allowed a resurgence of soil mapping to occur. This funding enabled soils contained under parts of northern Tasmania's State Forest to be characterised and mapped, to provide relevant information for the management of forest soils. This five year project allowed a further c. 153,400 ha to be investigated at a scale of 1:100,000 (Grant *et al*, 1995; Hill *et al,* 1995; Laffan *et al*, 1995).

During a similar time period, soil investigation was also occurring within two agricultural regions. Doyle (1993) surveyed the South Esk region in northern Tasmania, while Holz (1987) studied and mapped soil properties for regional irrigation development in the Coal River Valley in southern Tasmania.

In all three phases of soil investigations, the role of soil parent material has been highlighted as a dominant soil forming factor in Tasmania. The diversity of lithologies present has led to a wide range of soil parent materials; ranging from highly siliceous through to mafic materials with a broad variety of textures ranging from sands through to clays. Only ultra-mafic soil parent materials are absent. The dominance and diversity of the lithology within the landscape led to the mapping and taxonomy of soils commonly based on rock type e.g. 'Brown soils on dolerite'.

Grose *et al* (1999) along with Doyle and Farquhar (2004) commenced investigations on how different soil types and soil parent materials influence grapevine growth. These studies highlighted that a broad range of soil types were being utilised for vineyard production in Tasmania and there was no one clear soil type identified as producing more quality wines than another. Examples of the wide variation in soils and geology are shown in Figure 2.

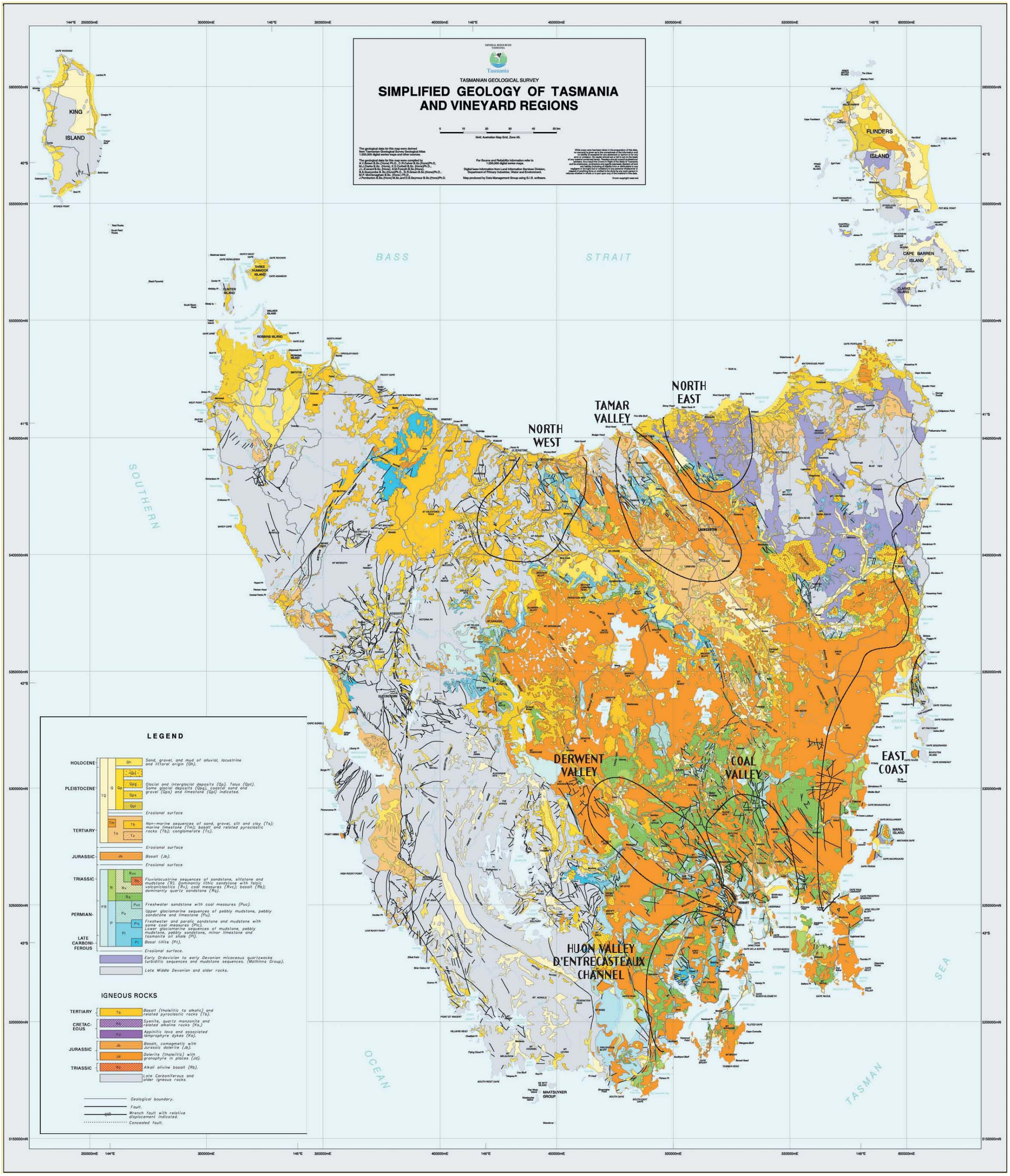

Figure 1: Simplified geology of viticultural regions of Tasmania. Reproduced with permission from Doyle and Farquhar (2004).

Figure 2: Examples of soils formed from different parent materials within Tasmanian vineyards. a) Podosol from siliceous sands with coffee rock subsoil (Meadowbank Estate); b) Dermosol from siliceous Triassic sandstone (Moorilla Estate); c) Mafic brown Dermosol on dolerite (Cragiow Vineyard); d) Mafic black Vertosol on dolerite (Roth Vineyard); e) Ferrosol from sesqueoxised weathered basalt (Pipers Brook Vineyard); and f) Brown Dermosol from windblown sand with calcareous sandy subsoil (Derwent Estate Vineyard). All photos courtesy of Richard Doyle and CSIRO Division of Soils.

Soil properties and vine performance

Grape vines (*Vitis vinifrera*) are grown in a broad variety of environments. Throughout the literature there is the perception that vines prosper in poor soil environments (Dickenson and Salt, 1982) and that the best wines are thought to come from soils that are too poor for other crops (Van Leeuwen and Seguin, 2006). Improved wine quality on poorer soils is assumed to result from a reduction of yield and/or canopy shading rather than resulting from any inherent soil property (Amerine *et al*, 1980; Dry and Loveys, 1988; Dry *et al*¸1990; Smart and Robinson, 1991). Root growth however, is directly influenced by the properties of the soil environment (Cass, 2004; Lanyon *et al*, 2004) and as most of the required nutrients and moisture needed for plant growth are taken up via the root system, the properties of the soil have considerable influence on above ground growth. Soil properties can also influence the ability of the root to function efficiently. Cass (2004) outlines that either a lack of water or lack of oxygen within the soil profile can decrease the uptake of nutrients by the roots, as do areas of high penetration resistance.

It is commonly believed that the growth and vigour of the vine canopy is a direct reflection of the size and health of the vine root system (Saayman and Van Huyssteen, 1980; Van Huyssteen, 1988; Smart 1995; Southey 1992). The size and vigour of the canopy also has an impact on berry quality, thus growth and development of the root system has a strong bearing on the overall wine quality. Excessive vine vigour has long been held responsible for reducing wine quality by reducing air movement through the canopy and/or shading of fruit. Consequently an extensive root system has also been perceived as detrimental to wine quality (Smart and Robinson, 1991). This, in turn, has reinforced the belief that the best wines come from poor soil environments. However, vines with a restricted root system and canopy do not necessarily produce the highest fruit quality (Van Huyssteen and Webber 1980). Understanding optimum soil conditions for grapevine root growth and distribution is important for the production of high quality wine. Despite this, research into root distribution and root function is the least understood part of viticultural production (Cass, 2004) and currently, little is known about the relationship between grapevine root distribution, vine growth and wine production.

The soil environment influences the spatial distribution of grapevine roots (Southey, 1992) through both physical characteristics (Saayman, 1982; Richards, 1983; Van Zyl, 1984; Van Huyssteen, 1988a) and chemical properties (Marcelin, 1974; Conradies, 1983). Rankin *et al* (1971) concluded that the most important soil features for vine performance include soil depth, water-holding capacity and soil drainage, rather than soil nutrition. Seguin (1986) and Van Leeuwen *et al* (2004) also support the notion that there is no direct relationship between soil fertility and fruit quality. Rawson (2002) has demonstrated evidence of soil 'fingerprinting' whereby consistent patterns were established between berry composition and soil type, however he was unable to determine direct matches with specific soil properties. Regardless, he demonstrated that soil chemical characteristics do influence the fruit quality. Conradie (2002) also indicates that the chemical composition of the soil not only influences vine growth, but also influences the quality of fruit and wine produced. Therefore both the physical and chemical composition of the soil has been shown to have an influence on overall viticultural production.

There have been many attempts to outline the ideal soil conditions for vine growth with many good summaries produced within Australia (Cass *et al*, 2002; Gladstones, 1992, 2012; Lanyon, 2004; Northcote, 1988; White, 2003; White 2010) however few have detailed observations pertaining to root distribution.

Soil physical properties

Many studies show a correlation between wine quality and soil physical properties; namely soil structure, macroporosity, drainage and soil texture (White *et al* 2007; Goode, 2005; Norman 1992; Seguin, 1986; Guilloux, Duteau and Seguin, 1978, Rankin *et al*, 1971). All suggest that the benefits of good soil structure result in increased root distribution and improved access to soil water. The main components reviewed here are soil depth, strength and structure and the influence they have on water relations and the uptake of nutrients.

<u>Soil depth</u>

The depth of the soil profile directly limits the soil volume that any roots have to access stored moisture and nutrients. In classical terms, soil depth refers to how much solum (A and B horizons) is present above the underlying regolith or unweathered bedrock. However vines do root into weathered or fractured bedrock and regolith beneath the solum. Soil solum depth available can also be reduced by hostile soil conditions such as high penetration resistance or adverse soil chemistry (White, 2010). Regardless of the type of restriction, insufficient soil depth has been shown to be a major limitation to root distribution which results in reduced grapevine vigour (Saaymann and Van Huyssteen, 1980; Cass *et al*, 1993). Coipel *et al* (2006) argues that soil depth is more important than soil type in determining wine quality. Studies undertaken in South Africa show vine growth increased linearly with increasing soil depth (Van Huyssteen, 1983). They categorised soil depth into three groups; depths around 60 cm had vines with normal growth, 40 – 60 cm deep soils had poor growth, and soils that were less than 40 cm deep where insufficient to sustain live grapevines. Modification of the effective soil depth through ridging and mounding (Myburgh *et al*, 1998) or deep ripping of compacted soils (Conradie *et al*, 1996) was shown to be beneficial to vine performance. In Australia, research conducted in the McLaren Vale and Hunter Valley has shown deep ripping shallow soils to fracture impeding layers and/or the underlying bedrock was an effective way to increase the available volume for root exploration (Myburgh *et al*, 1998; White, 2010).

Conversely, deep soil profiles are often associated with excessive vine growth, particularly where access to moisture and nutrients are unrestricted (White, 2009). However when soil fertility is low, root access to a large soil volume is required for sufficient nutrient uptake for vine growth. Seguin (1986) highlights the importance of extensive root growth for many of the best growing provinces in France (e.g. the Medôc region), particularly as these regions do not allow supplementary irrigation and that vines need to access stored soil moisture. In these regions, the interaction between soil depth coupled with the properties of the underlying bedrock determine root access to both moisture and nutrients. Where the underlying bedrock is highly fractured, grapevines can adequately grow in shallow soils as the rootzone can extend into the fractured substrate. Where the bedrock has few cracks or fissures, the overlying soil depth needs to be thicker for comparable vine growth to be achieved (Wilson, 1998). Therefore while there is a general trend of increased vine growth occurring in deeper soils, the actual depth required for optimal vine growth will depend on the soil and rock types and will not be consistent between viticultural regions. For this reason Van Huyssteen (cited in Smart and Robinson, 1991) concludes "without experience, it is almost impossible to predict beforehand what soil depth will result in the optimal vigour for a particular site and soil type".

Soil texture and structure

One reason for the unpredictable relationship between soil depth and vine growth is due to other soil constraints such as soil texture and soil structure. Soil texture describes the size distribution of the mineral particles (< 2 mm) within the soil, whereas soil structure describes the way these particles are arranged into larger units and the associated pore structure and planes of weakness that occur (McDonald *et al*,1990). Different structural sizes can exist together within one horizon and some structural units can cross into adjacent horizons. The type of particles and their arrangement into structural units influences many of the physical, chemical and biological aspects of soil function. Examples of these include soil strength, soil aeration as well as water and nutrient movement (Dexter, 1988; Northcote, 1988; Kay 1990; Rose, 2004).

Kirchhof *et al* (1991) demonstrates that grapevines are markedly chemotropic, with root growth only occurring in suitable environments. The concept of chemotropic growth is very important when considering the role of soil structure on root distribution. Strongly structured soils (particularly reactive clays) may have soil peds that that could inhibit root growth, thereby dramatically reducing the soil volume available for root growth and nutrient extraction. Studies by Van Huyssten (1986) noted that grapevines did not show compensatory growth such that management needs to respond to subsoil limits to root growth through improved soil conditions for root growth (Kirchhof *et al*, 1991). Increased vegetative growth and vigour have been shown to be linked to increased root growth (Conradie 1983; Saayman and van Huyssteen 1981). Zhang *et al* (2001) demonstrated in a glasshouse trial that both root and above ground growth was negatively affected by root restriction. As the degree of restriction increased (i.e. smaller pot volume) the root size distribution was altered with greater abundance of more fine roots and less medium sized roots.

<u>Soil strength</u>

The strength of the soil is highly dependent on moisture content and soil texture, with highest strengths usually occurring when the soil is dry and compacted (Cass *et al*, 2002). Soil strength is commonly measured through the use of a penetrometer which measures the force required for a cone or head of known area to penetrate through the soil matrix. Penetrometer resistance values are used to indicate the ease or difficulty of root elongations (Barley *et al*, 1965). The critical penetration resistance value that limits grapevine root elongations is reported to be 2 MPa when measured in soils with field capacity moisture content (Myburgh *et al*, 1996; Van Huyssteen, 1983). Cass *et al* (2002) suggests amelioration by tillage if penetration resistance exceeds 3 MPa at any soil moisture content. Penetration resistance is closely related to soil density. The critical bulk density for grapevine root growth has been suggested to be either 1500 kg/m^3 (Penkov *et al*, 1967) or 1700 kg/m^3 (Van Huyssteen, 1988). Ferree and Streeter (2004) demonstrated that soil bulk density affected vine growth by reducing leaf number, leaf area and shoot length. While root growth has been demonstrated to be severely restricted when soil strength is greater than the critical values of either penetration resistance or bulk density, no value of either has been shown to completely impede vine root growth (Penkov *et al*, 1967; Van Huyssteen, 1988). Nagarajah (1987) suggests that root growth, when soil strength is greater than these critical values, may occur through old root channels, soil fracture lines and voids.

Viticultural management demands a high level of tractor traffic for the application of sprays (herbicides and pesticides), fertilisers and also the use of tillage to mechanically remove undervine weeds. This traffic can result in increased in soil compaction. Subsoil compaction is attributed to wheel load (Dijck and Asch, 2001) and has been shown to affect soils to 45 cm and possibly 60 cm depth (Van Huyssteen, 1983). High levels of compaction can occur after just one pass of the vehicle such that it is recommended that wheel tractors should not be used at all in vineyards for at least one year after vine establishment (Van Huyssteen, 1983). It is expected that few vineyards would have followed this recommendation (especially modern ones). With an increasing number of vineyards becoming 'organic' and using mechanical means to reduce weed load (rather than chemical) the potential for increasing compaction from increased machine traffic is quite high. Van Huyssteen and Weber (1980) showed that in vineyards under continuous mechanical cultivation develop very high soil strengths in the inter row beneath the tractor wheels. This has been shown to compact the soil to such an extent that it was a barrier to root growth (Schulte-Karring 1976) and often limits root exploration to directly below the vine mound.

Soil strength increases dramatically with a decrease in soil moisture (Cass, 2004; Cass and Baumgartner, 2010; Van Huyssteen (1983). Therefore it is important that measurements of soil strength, i.e. penetrometer testing, only be done at moisture contents close to field capacity – or at least comparisons between sites be done at the same moisture content.

Water movement, storage and availability

As eluded to with the discussion of soil depth, the ability of the vine to access soil moisture is one area that has received considerable attention in literature and within viticultural management practices. Lack of soil moisture is a major constraint to grapevine growth and development within Australia (Lanyon *et al*, 2004). While this is mainly due to climatic limitations such as low rainfall, it is the physical properties of the soil (such as structure, texture and depth) that determine how much moisture is stored and accessible to plant roots. Many wine growing regions in Australia and other 'New World' regions (such as New Zealand, South Africa and the United States of America) use supplementary irrigation to overcome limited soil depth or soil moisture availability. Much of the literature from these regions focuses on methods for monitoring soil moisture and 'optimal' scheduling of irrigation. In contrast, the 'Old World' viticultural regions (such as France) are prevented from using artificial irrigation on grapevines. In these regions, most of the literature and management focuses heavily on soil characteristics to store moisture, such as soil depth and bedrock characteristics. The use of irrigation to overcome limited soil moisture has enabled many New World developments in areas that would otherwise be considered marginal. In this way there is a growing perception that soil moisture constraints can be overcome with technology.

Soil structure has a profound effect on water infiltration, drainage and ultimately the distribution and storage of water within the soil profile. Hardie (2011) demonstrated that water movement through dry texture contrast soils (Sodosols and Kurosols) is dominated by preferential pathway systems. These pathways exist due to a combination of water repellency and subsoil shrinkage cracks. In these soils, much of the water entering the soil profile occurs via non-uniform mechanisms which lead to non-uniform storage of water within the soil profile. Spatial variation in soil moisture storage also occurs under drip irrigation as water is not uniformly applied to the soil surface. This has been highlighted by Stevens and Dougles (1994) and van Zyl (1988) who both compared rooting patterns between drip irrigation and micro-jet irrigation methods. Both studies found that roots of drip irrigated vines were concentrated along the vine row compared to an even spread of roots from the micro-jet irrigation. It was also observed that the root density was lower directly beneath the position of the dripper. It was hypothesised that this was due to periodic oxygen shortages in these regions (van Zyl, 1994). In unirrigated regions of the soil profile, root growth primarily occurred in spring and autumn when soil moisture was sufficiently recharged from natural rainfall events (van Zyl, 1994). It was therefore speculated that root distribution was largely modified in areas that relied on irrigation.

Soil strength may also limit the availability of stored soil moisture. The strength of the soil matrix generally increases as soil moisture declines (Cass *et al*, 2002), therefore as moisture becomes scarce root access to the moisture may also become mechanically impeded. This concept has been described as the 'non-limiting water range' (NLWR) by Lefey (1985) and as the 'least limiting available water' (LLAW) by de Silva and Kay (1996). In both concepts the amount of moisture available at high water content is controlled by the macroporosity of the soil and its relation to aeration and the lower limit is determined by the water content at which either the soil strength becomes too great for root elongation, or where soil moisture is held at tensions greater than the plant can extract. Consequently as the soil becomes drier, further soil water extraction becomes progressively more difficult as root exploration becomes increasingly impeded.

The LLAW concept has been applied to viticulture by Cass and Baumgartner (2010). They used the LLAW to classify viticultural regions in California. While White (2010) suggests the LLAW approach could be useful for Australian vineyards, the LLAW concept relies on measurement of soil physical properties (such as bulk density and the soil water characteristic curve) which are not routinely measured in traditional soil surveys. Cass and Baumgartner (2010) suggest that the lack of soil physical data can be overcome through the use of pedotransfer functions in which commonly measured soil parameters are used to predict more complex soil physical properties through statistical correlations. McKenzie and Cresswell (2002) outline how these estimates can be obtained in more detail. This approach could be useful due to the spatial variability of soil properties that exists within a landscape, down a soil profile, as well as over time. Clearly, understanding the physical properties of a given soil profile is needed when observing any variation in grapevine root distribution.

Water availability and vine performance

Freely available water within the root zone can lead to excessive vegetative growth within vines (Smart and Robinson, 1991). Vines with large and dense canopies can reduce the efficiency of photosynthesis within the leaves (Smart, 1974) and reduce fruitfulness (Jackson and Coombe, 1988). Fruit colour and berry components have also been shown to be adversely influenced by excessive vegetation (Bravdo *et al*, 1985; 1986). Conversely, excessive moisture stress is also detrimental to grapevine growth and fruit production. Depending on the timing and duration of the stress, lack of moisture can lead to abscission of flowers or leaves (Hardie and Considine, 1976), reduce yield by restricting cell division and expansion of berries (McCarthy, 1997; Matthews *et al*, 1987; van Zyl, 1984) and incomplete fruit ripening (Van Huyssteen and Webber, 1980). It is therefore advocated that a steady, moderate availability of moisture is the ideal for highest fruit quality (Seguin, 1986; Gladstone, 1992).

Stevens *et al* (1995) surmised that a mild water stress may supress vegetative growth and enhance sugar accumulation in berries. Mild water deficits have also been shown to help reduce berry size (Smart, 1974) and have positive effects on anthocyanin and tannin content of the skin of red grape varieties (Hardie and Considine, 1976; Matthews and Anderson, 1988; Koundorras *et al*, 1999).

Cass *et al* (2002) has proposed a set of critical limits for available water and how they are expected to influence vine growth (Table 1). White (2010) has compiled values for determining suitable plant available water values for grapevines from a range of different soil textures (Table 2). In order for viticulturists to utilise these values understanding the effective rooting depth must also be known. This is especially important when evaluating different soil types. Considerable effort in collecting and interpreting of water storage, root distribution and climatic effects on vine performance is still needed for Australian soils (Lanyon *et al*, 2004).

Table 1: Critical limits for available water in vineyards (from Cass *et al*, 2002)

Criterion	mm of water in the effective root depth		
	TAW	SAW	RAW
Very high (excessive)	> 200	> 150	> 100
High (high)	150 – 200	110 – 150	75 – 100
Moderate (optimum)	100 – 150	75 – 110	50 – 75
Low (sub-optimum)	50 – 100	38 – 75	25 – 50
Very low (insufficient)	< 50	< 38	< 25

TAW – total (plant) available water
SAW – stress available water
RAW – readily available water

Table 2: Plant available water (PAW) values for soils of different texture. From White (2010)

Soil texture	Plant Available Water (PAW) (mm/cm of soil)
Sand	0.80*
Loamy sand	0.86
Sandy loam	1.15
Sandy clay loam	1.43
Clay loam	1.48
Heavy clay	1.20

* value for sand is estimation only

Soil chemical properties

The role that soil chemical properties have on influencing both vine and root growth has often been concluded to be secondary to soil physical characteristics (Rankin *et al*, 1971; Seguin, 1986; Van Leeuwen *et al*, 2004). Research on soil chemical constraints to vine growth have mainly focused on hostile soil conditions such as low soil pH, high soil salinity and/or high soil sodicity. Very little research into how the soil nutritional status influences vine performance has been undertaken (Lanyon *et al*, 2004). Instead, research has mainly focused on hostile chemical characteristics of specific soil horizons.

<u>Soil nutrition</u>

In a review of conditions for grapevine growth, Gladstones (1992) concluded that there was a lack of objective evidence to relate vine growth with soil nutrient availability. Almost two decades later, White (2010) arrived at a similar conclusion when trying to summarise benchmark soil values. Much of the difficulty in relating soil nutrition to vine performance was attributed to the complex relationship between the root system and the soil (Lanyon *et al*, 2004). White (2010) suggested this difficulty was due to the highly variable spatial distribution of nutrients within the soil which was not accounted for during soil sampling. Knowledge of the root distribution in the soil can be used to guide soil sampling for nutritional analysis. Bramley and Hamilton (2006) also argue that the understanding of the spatial distribution of soil is rarely fine enough to relate soil chemistry characteristics to vine performance.

Soil moisture status influences the uptake of nutrients (Calo, 2002; Cass, 2004; Cookson *et al*, 2006; Schreiner, 2005; Van Leeuwen *et al* 2003) such that differences in nutrient availability may occur at similar soil concentrations depending on soil moisture distribution. Soil nutrient availability also vary considerably throughout the season (e.g. nitrogen as either NH_4^+, NO_3^-; phosphorus, $H_2PO_4^-$, HPO_4^{2-}; sulphur, SO_4^{2-}) and therefore require monitoring over time to determine seasonal variation in nutrient availability.

Both Cass *et al* (2002) and Lanyon *et al* (2004) have outlined benchmark criteria of soil nutrient and chemical status for viticultural production. Table 3 outlines many of these criteria. The noticeable omission from this table is ideal concentrations of exchangeable cations. While Cass *et al* (2002) and Lanyon *et al* (2004) suggest ideal values for exchangeable cations (namely Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}), both provide values using the saturation ratio concept outlined by Albrecht (1975). This concept has subsequently been discredited by Kopittke and Menzies (2007) who conducted a comprehensive review of literature and concluded that there is no ideal ratio between basic cations for optimal plant growth. Instead, the onus should be on providing sufficient but not excessive levels of each basic cation (Kopittke and Menzies, 2007). Subsequently within this thesis, nutrient requirements and/or deficiencies will be presented on a concentration basis rather than a ratio basis.

Table 3: Suggested benchmark criteria for soil nutrient and chemical status for wine production (reproduced from Lanyon *et al*, 2004)

Nutrients	Concentration range in soil (mg/kg)				
	Deficient	Marginal	Adequate	High	Toxic
NO_3-N	< 1	1 – 2	2 – 10	> 10	
K	< 50	50 – 100	100 – 250	> 250	
P	< 25	25 – 35	35 – 80	> 70	
Cu	< 0.1	0.1 – 0.2	0.2 – 0.4	> 0.4	> 2
Zn	<0.5	0.5 – 1	1 – 2	2 – 20	> 20
Mn		< 2	2 – 4		
Fe			> 4.5		
Al					> 100
B	< 0.1		0.2 – 1.0		> 3.0
S	< 10				

Method of determination:
K, P – Colwell bicarbonate extractable
Cu, Zn, Mn, Fe – DPTA extractable
Al – ammonium chloride extract
B – hot water extract

Soil pH

The pH of the soil is considered important due to the affect it has on the availability of other nutrient elements (Baligar, 1998). The influence or association of soil pH on causing elemental deficiencies (N, P, K, Ca, Mg, B, Fe, Cu, Mn, Mo, Si and Zn) and toxicities (Al, Mn, Fe, S, B, Co, Mo, Na) are well recognized (Baligar and Duncan, 1990; Clark, 1982). As grapevines are successfully grown on a wide range of soil types it has been claimed that soil pH is not critical (Seguin, 1986; Winkler *et al*, 1974). However it has been demonstrated that vines respond negatively to a soil pH below about 5 (Cass, 1988; Conradie, 1983; Delas, 1984) as well as to soil pH values above 8.3 (Davidson, 1991; Gelat, 1996; Saayman, 1981). Therefore the recommend pH range for grapevine production is generally suggested to be 5.5 to 8. However, some confusion exists over the method used to determine the pH value with White (2003, 2010 both citing Cass, 1998) who recommended this range refers to a 1:5 soil:water extract, whereas both Cass *et al* (2002) and Lanyon *et al* (2004) recommend this range occurs using a 1:5 soil: 0.01 M $CaCl_2$ extraction, with Cass *et al* (2002) recommending a pHw range of 6.0 to 9.0. Regardless of the methodology the literature demonstrates that grapevines can tolerate a wide range of soil pH.

If the soil pHw decreases to less than 5.2, aluminium becomes increasingly soluble with the species dominated by Al^{3+} (Marion, 1976). The now soluble Al^{3+} is rapidly taken up by vine roots were it then interferes with the uptake and utilisation of many other nutrients including phosphorous, calcium and magnesium (Roberts, 2005). High levels of exchangeable Al^{3+} are considered toxic and are generally associated with inhibited root growth within soils of low pH (Foy, 1992; Baligar, 1998). As low soil pH and high exchangeable Al^{3+} generally occur within subsoils, the root growth of many plants is limited and generally leads to a shallow root system (Foy, 1974). In studies of vine growth on soils with low pH subsoils, high levels of exchangeable aluminium have been demonstrated to inhibit vine root growth within the subsoil horizons causing vines to have a shallow root system (Himelrick, 1991; Baligar, 1998; Conradie, 1988; Delas, 1994, Sumner, 2005). Sumner (2005) describes toxic aluminium conditions as causing characteristically ‘crinkled’ vine root systems or ‘stubby root syndrone’.
The critical value of exchangeable Al^{3+} is suggested to be 100 mg/kg (Table 3, Cass *et al*, 2002; Roberts, 2005) however Delas (1984) recommends a critical value of 50 mg/kg.

In soils with high pH (> 8.0) the availability of nitrogen, calcium, magnesium, iron, manganese copper and zinc are all reduced (Saayman, 1981; Davidson, 1991). These soils may have elevated concentrations of carbonates which may also cause iron deficiencies (lime-induced chlorosis) due to high concentrations of bicarbonate ions reducing the concentration of ferric iron and inhibiting iron uptake by the vines (Gelat, 1996). The use of adapted root-stocks can help overcome this limitation.

Salinity

Grapevines are classed as moderately sensitive to salinity (Shani & Bengal 2005, Dowton 1977, Mass and Hoffman 1977) with adverse vine growth resulting from the uptake of Na^+ or Cl^- ions (Mass and Hoffman, 1977). The effect of soil salinity as expressed by electrical conductivity (EC) on vine growth has been outlined by both Cass *et al* (2002) and White (2003) and a summary of their recommendations are shown in Table 4.

Irrigation with saline water has been shown to increase chloride concentrations in the leaf, reducing leaf photosynthesis and ultimately reducing vine vigour and fruit yield (Prior *et al* 1992a, 1992b). In which, the reduction of photosynthesis and the level of leaf damage is proportional to the leaf chloride concentration (Thomas 1934; Downton 1977; Stevens and Harvey 1995). Different rootstocks have differing susceptibilities to chloride due to differing efficiencies of excluding chloride (Downton 1985) such that threshold chloride levels have been established for different rootstocks (Zhang *et al,* 2002). The use of different rootstocks is a common way of overcoming salinity during site establishment (Dry and Smart, 1988). However, this is only possible if soil salinity is identified prior to planting. The ability of grapevine roots to exclude both sodium and chloride is greatly reduced by a short period of waterlogging (West and Talyor 1984). Even when soils receive irrigation with a low salt load, there is a tendency for salts to accumulate within the profile. The recommended management for dealing with the increase in salts is a periodic 'flushing' either by using high quality water (low salt level) or by a greater irrigation volume (White, 2003). The intention of which is to move the salts deeper in the profile and below the root zone. For this to be able to occur, the soil needs sufficient depth and porosity to enable the excess water to drain. While most drainage systems are designed to prevent the formation of a permanent watertable, they may not prevent the formation of a temporary or perched watertable following irrigation. Stevens and Harvey (1995) however, suggest that if the vines are actively growing, then the advantage gained from a 'flushing' irrigation may be reduced or even lost due to the onset of temporary waterlogging. This has implications to where either irrigation application is uneven or where uniform application of water is applied to changing soil types across a vineyard block. In both cases, localised waterlogging may occur even under 'deficit' irrigation practices. An increase in perched soil water could help to increase mobilisation of salts from deeper in the profile, thus an increase in salt stress may be seen. Therefore if a flushing irrigation is to be applied, it will be more effective when the plants are dormant (Stevens and Harvey, 1995).

Table 4: Criteria for soil salinity and potential yield reduction for vines (compiled from Cass *et al*, 2002 and White, 2003)

Salinity hazard	ECse (dS/m)	Effect on grapevine growth	Reduction in vine yield (%)	$EC_{1:5}$ (dS/m)				
				Loamy sand	**Loam**	**Sandy clay loam**	**Light clay**	**Heavy clay**
Non-saline	< 2	Negligible effect on vines	< 10	< 0.15	< 0.17	< 0.25	<0.30	< 0.40
Slightly saline	2 – 4	Own-rooted vines start to be affected	10 – 25	0.16 – 0.30	0.18 – 0.35	0.26 – 0.45	0.31 – 0.60	0.41 – 0.80
Saline	4 – 8	Own-rooted vines severely affected but some rootstocks are more tolerant	25 – 50	0.31 – 0.60	0.36 – 0.75	0.46 – 0.90	0.61 – 1.15	0.81 – 1.60
Very Saline	8 – 16	Vines cannot be grown successfully	> 50	0.61 – 1.20	0.76 – 1.45	0.91 – 1.75	1.16 – 2.30	1.61 – 3.20
Highly saline	> 16	All grapevines will die	-	> 1.20	> 1.45	> 1.75	> 2.30	> 3.20

ECse is saturated paste electrical conductivity, $EC_{1:5}$ is the corresponding approximate electrical conductivity of a 1:5 soil:water extract for the various soil textures.

Sodicity

Within Australia, soils are classed as sodic when the proportion of exchangeable sodium exceeds 6 % of the total cation exchange capacity (Isbell, 1996). This limit is lower than the threshold adapted for classification of sodic soils in the United States (US Soil Taxonomy) which classes soils as sodic when the exchangeable sodium percentage (ESP) exceeds 15 %. The lower ESP for sodicity in Australian soils is attributed to the low concentrations of soluble minerals in the soil solution that are necessary to maintain the salt concentration during leaching (Northcote and Skene, 1972).

High soil ESP is generally associated with poor vine growth due to the tendency for sodic soils to have poor soil structure. Several studies have demonstrated grapevine growth is reduced in high ESP soils (Khanduja *et al* 1980; Samra 1986). However, no critical value for grapevine performance has been promoted in the literature, other than those for minimising soil degradation (ESP of < 6% Australia, or < 15 % USA). However, the deleterious effect of high ESP on soil structure is not universal in all soil types or conditions. Rengasamy and Olsson (1991) demonstrate that increased soil salinity can mitigate the dispersive properties of sodic soils, thus stabilising the soil structure. Therefore assessing potential vine root growth using only ESP may give an incorrect assessment of the dispersion risk. Lanyon *et al* (2004) conclude that more work is needed on the consequences of soil sodicity on vine performance.

Grapevine root morphology

Plant roots are invariably hard to study due to their tortuous growth through soil and, in the case of perennial plants, roots can grow to considerable depths. Substantial effort is generally required to observe and accurately measure root growth and distribution as the observation normally involves some level of soil excavation. One reason that there have been many studies on the influence of above ground management on vine growth and fruit yield is that below ground studies are generally very time consuming, difficult and expensive to undertake.

The study of roots is essential as roots supply most of the water and nutrients for the above ground parts of the plant. They also synthesise hormones needed for adequate development of shoot growth (Richards, 1983). The main aim of acquiring an understanding of root growth and root function is to improve management of shoot growth as well as yield and berry quality. Therefore knowledge of root growth, root function and the rooting environment (i.e. soil) is needed to better select sites or manage existing sites more effectively.

As grapevines are perennial plants, they tend to have extensive lateral and vertical spreads of roots of many metres in length especially in well structured, loose and deep soils (3 m to > 8 m from trunk) which makes it difficult to observe the entire root system (Seguin, 1986; Smart *et al*, 2006). Grapevines are commonly thought to have a relatively low root density within the soil (Morano, 1995), however a wide range of root densities have been reported within the literature. These range from between 0.01 to 0.1 cm/cm^3 (Nagarajah, 1987; Randall and Coombe, 1978), 0.3 to 0.8 cm/cm^3 (Stevens and Douglas, 1994; Stevens et al., 1995) or 1.9 to 4.9 cm/cm^3 (Dowley *et al*, 2002; Tisdall *et al*, 1984). In all studies, higher root densities were recorded in the topsoil compared to the subsoil. Grapevines have been reported to have:

1) lower root density than other woody plants (Richards, 1983; Smart and Coombe, 1983);
2) similar root density to other woody plants (Stevens and Douglas, 1994; Stevens et al., 1995); or
3) higher root density than other woody plants (Dowley 2002; Tisdall *et al*, 1984)

Dowley *et al* (2002) demonstrated that variations in root density were most likely caused through the different methods used to determine root length density. Manual root separation methods produce low root length densities whereas soil dispersion methods tend to produce higher root length densities (Dowley *et al* 2002). This creates a further layer of complexity when reviewing different studies of root distribution and vine performance.

Smart *et al* (2006) provides a comprehensive review of grapevine root distribution and highlights that highest root growth occurred within the topsoil horizons with root numbers generally declining with depth, with most roots (80 %) occurring at depths less than 1 m. This review also highlighted how similar the vertical root distributions of grapevines are, regardless of genotype or climatic differences. However, the majority of the observations used in this review were from relatively deep, fertile soils and there is a need to understand how root distribution is influenced on more marginal and diverse soil types, such as shallow or infertile soils or soils with unusual soil chemical characteristics (Smart *et al* 2006). Similarly, how root distribution is influenced by soils with structural impediments also requires further investigation as well as how it is affected by management practices such as ripping and/or irrigation.

Methods of Root Observation

Various methods have been developed to measure or observe root growth (Bohm, 1979; Smit *et al* (2000). These methods include measurement of root length, branching pattern, vertical distribution (including rooting depth and/or effective rooting depth) and horizontal distribution. However it is recognised that no one technique can inform all these aspects of root growth (Bohm, 1979; Harper *et al*, 1991; Mackie-Dawson and Atkinson, 1991). It is therefore necessary to consider the reason for measuring roots before deciding on an appropriate methodology. Mackie-Dawson and Atkinson (1991) conclude that the main selection criterion is whether the reason for measuring is to observe changes over time or whether spatial data on distribution at one moment in time is adequate. When multiple measurements over time are needed then an observational method should be used (e.g. minirhizotron), however if spatial distribution is needed then a direct sampling method is best (e.g. soil cores or soil profile wall methods). The different methods can generally be divided into one of two groups as outlined below:

1. Methods that provide information on patterns of root distribution:
   - Whole plant excavation
   - Soil profile wall methods
   - Soil cores (e.g. core-break method)
   - Isotope applications
   - Resin embedding techniques
   - Nuclear magnetic resonance (NMR)

2. Methods that allow assessment of roots over time:
   - Rhizotrons
   - Minirhizotrons
   - In-growth bags

Generally, methods that allow monitoring over time are less destructive to the soil profile and allow a higher number of replicates than root distribution approaches. However, a drawback of these methods is a limited understanding of interaction with soil properties, as only a small portion of the soil is measured. Methods that provide information of root distribution patterns overcome these limitations by making observations over a larger area (e.g. soil profile wall methods) but this generally reduces the amount of replicates that can be undertaken.

The focus of the present study was to understand the spatial root distribution throughout the soil profile so a direct measurement method was appropriate. The profile wall technique was selected as there was also needed to observe soil profile characteristics. A soil trench would therefore already be exposed and would enable the interface between root and soil to be observed over the soil pedon. The consequence of this method is the lack of capacity for replication resulting in the lack of data for statistical analysis. However it was concluded that the detail gained but studying the soil and root interface over a large area outweighed this deficiency in the method.

3. General Methods

General site selection

Due to the nature of this project, the selection of the studied sites was critical to ensure both vine and root growth variations were due to the soil resource. While high variation of both vine growth and soil type were readily observed within vineyards, differences in variety, clone, trellis or vineyard management excluded areas from inclusion. Therefore a meticulous set of selection criteria was established to minimise any environmental and cultural influences, as outlined below:

- own-rooted grapevines with same variety and clone;
- vines of same age, with vines being not younger than 5 years;
- identical row and vine spacing;
- identical soil management;
- identical canopy management, pruning and harvesting techniques; and
- located within a small geographical area to minimise mesoclimatic variation.

Infra-red imagery of plant cell density (i.e. vine vigour) was used to identify vineyard variability when available, and to direct soil investigation within a vineyard.
Slope variations were more difficult to control as topography applies a strong influence on soil formation within Tasmania.

Plot location and layout

Using the constraints listed above, individual plots were located where changes in either plant growth or soil type were observed. Each plot consisted of one excavated soil trench per 12 vines as outlined in Figure 3. The soil trench was excavated parallel to the vine row and aimed to expose soil across two vines (i.e. the trench length was a minimum of twice the vine spacing). The trench was orientated parallel to the row and was excavated at a minimum distance of 450 mm from the vine row. The profile face was gently cleaned by hand to a distance of 100 mm from the vine row to expose fresh soil before measurement of root distribution and penetration resistance.

Trench width varied between 600 – 800 mm and was less than half the inter-row space. Trench width varied between vineyards due to the availability of excavators however trench width was consistent between plots within the one vineyard. If any topographic variation existed, the soil trench was excavated on the lowest end of the plot to prevent water collection when the trench was open and to reduce the possibility of disturbed soil influencing nutrients (mixing), water infiltration and storage when the trench was re-filled.

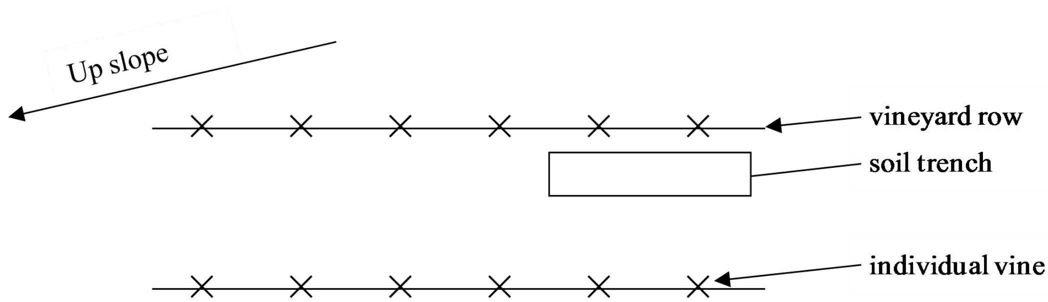

Figure 3: Plot layout detailing location of the soil trench relative to the measured vines.

Observation of root distribution

Root distribution was determined during winter by using the profile wall method outlined by Bohm (1979). This method of recording root distribution was chosen over others as it was determined that it was the most efficient way of describing the distribution pattern. As grapevines are capable of exploring a large volume and have a low root density compared to other perennial plants. Prior to recording root distribution, the profile face was gently excavated back a further 100 mm by hand leaving the roots exposed. Root distribution of two vines were recorded and classified into four different size classes (< 1 mm, 1 – 2 mm, 2 – 5 mm, > 5 mm) using a 5 x 5 cm grid. Observations of root interaction with soil also noted (e.g. crack, horizon boundary, within old root etc).

Soil characterisation and sampling method

Detail field descriptions of each soil profile was undertaken as outlined by McDonald *et al* (1990) and were classified according to the Australian Soil Classification (Isbell, 1996).

Soil was sampled for laboratory analysis by horizon boundaries. Samples were air-dried, the samples split with half ground to < 2 mm. All air dry soil was stored in air-tight zip lock bags.

Many profiles had large columnar primary structure that extended across horizon boundaries. For consistency, these were mainly described as prisms throughout the lower horizons with only the upper most horizon described as a columns if a rounded top was present (Figure 4).

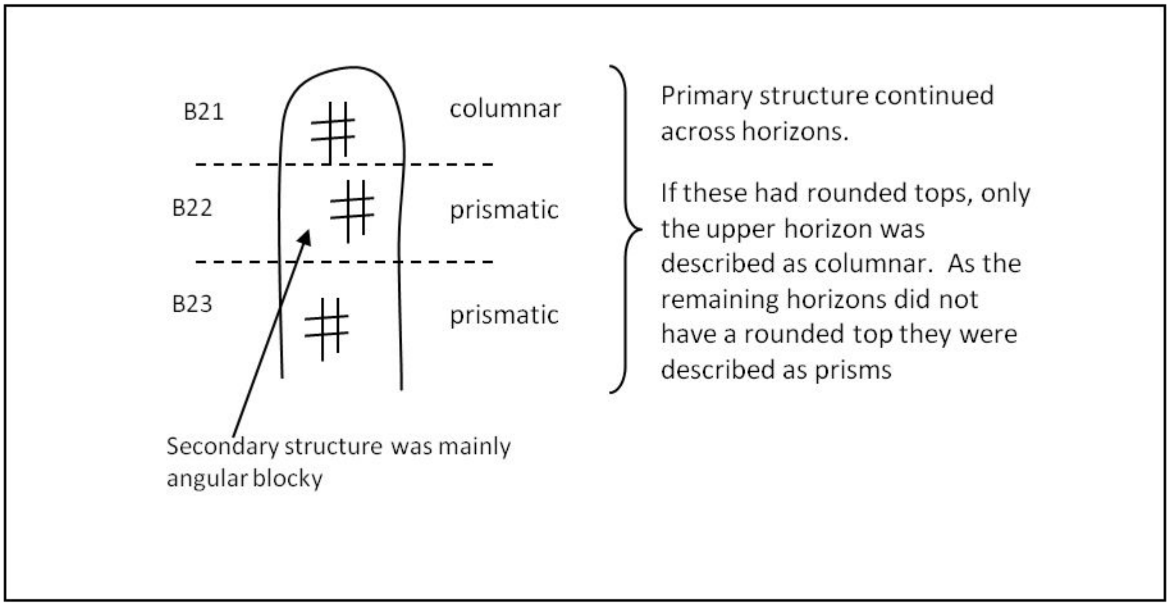

Figure 4: Diagram of soil structure description.

Penetration resistance

The measurement of penetration resistance was undertaken using a hand-held penetrometer (Penetrometer ST 207, with 6 mm dia head) across the profile face same 5 cm x 5 cm grid used for recording root distribution. This allowed detailed observations of soil structure and root growth to be compared to the soil penetration resistance. Penetration was measured on a freshly cleaned profile face to eliminate surface crusting of the soil.

Five measurements were taken for each cell of the grid to obtain an average cell value.

Estimation of plant available water

Plant available water (PAW) was calculated based on soil texture and used the conversion values of PAW (mm/cm of soil) outlined by White (2010) (see Table 2). Two PAW values were estimated. The first was calculated based on depth and was an estimation of PAW within the upper 1 m of the soil profile. The second calculation was based on observations of root frequency with the PAW value calculated for the soil depth that contained 90 % of all root observations.

Vine measurements

Yield and yield components

All the vines within each plot had fruit hand-harvested and individually weighed. Bunches were counted during harvesting to allow calculation of mean bunch weight per vine. The date of harvest was determined by each respective vineyard manager and all plots within one vineyard were harvested on the same day.

Pruning weight

Pruning weights were also assessed for each vine within the plots. Vines were pruned as per the standard vineyard practice which varied between vineyards (outlined in each individual methodology sections). Canes were counted prior to pruning and all pruned material less than two years of age was collected and weighed on electronic scales (resolution of 10 g). Mean cane weight was calculated by dividing the total pruning weight by the number of canes.

Remote sensing

Infra-red surveying

Where available, images of plant cell density (PCD) were provided from the respective vineyard managers. These digital multispectral images were supplied by SpecTerra Services Pty Ltd (Leederville, Western Australia), using plant cell density (PCD) as the vegetation index. PCD is a ratio of reflected near infrared radiation (NIR) to reflected red radiation (R):

$$PCD = NIR/R \text{ (Dobrowski et al., 2002)}$$

The near infrared waveband centred on 780 nm, and red light reflectance around 675nm. SpecTerra's post processing involves the use of a proprietary algorithm designed to remove pixels that do not contain information from the vine row itself, eliminating interference from reflectance of the interrow surfaces. These images were used to quickly discriminate areas of high and low grapevine vigour.

Electromagnetic Induction

The sites were free surveyed for electromagnetic induction using a hand-held EM-38. Measurements were taken in both the vertical and horizontal diploe at each plot position. The location of each plot were recorded via a hand-held GPS (accuracy +/- 3 m, datum GDA94) and maps were produced using Surfer v.8 (software by Golden Software) by gridding the point data using kriging.

Soil chemistry

Soil samples were air-dried and then disaggregated using a mortar and pestle before passing through a 2 mm sieve. The fine fraction was then split sampled to ensure the analysed sample was homogeneous. All samples were initially analysed for pH (1:5 soil:water & 1:5 soil:$CaCl_2$) and electrical conductivity (EC). The methods for subsequent cation analysis were selected depending on these results as outlined in Figure 5. An outline of methods used is listed in Table 5. Soil samples taken for investigations on Tertiary sediments (Chapter 4) were stored before being sent to CSBP laboratories (Bibra Lakes, WA) for subsequent testing.

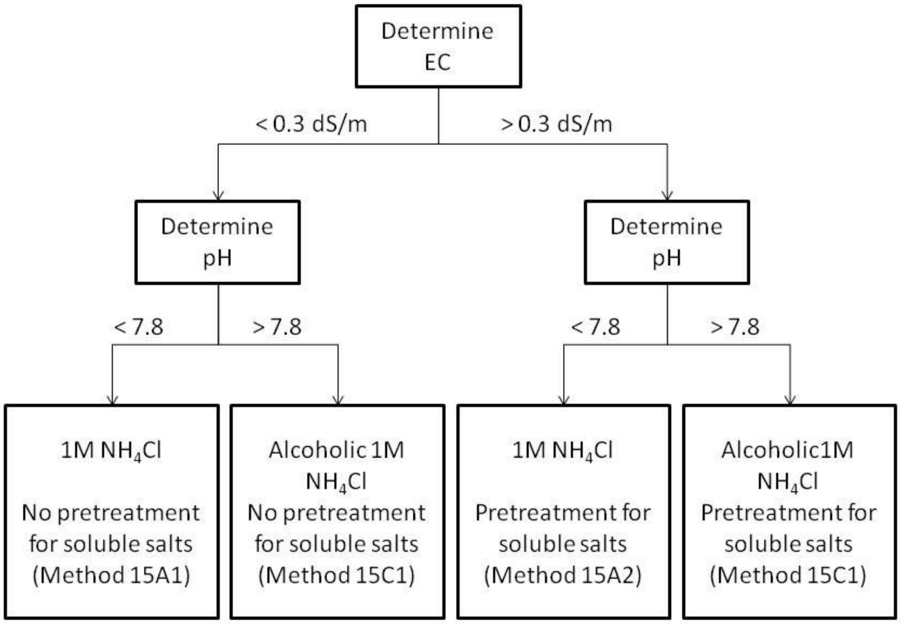

Figure 5: Flow diagram outlining the work flow for determination of cation analysis methodology

Table 5: Soil Laboratory Tests

Test Parameter	Test	Test Code	References
Soil Reaction	pH (1:5 soil:water)	4A1	Rayment and Higginson (1992)
	pH (1:5 soil:$CaCl_2$)	4B2	Rayment and Higginson (1992)
Electrical Conductivity	EC (1:5 soil:water)	3A1	Rayment and Higginson (1992)
Exchangeable cations	Ca		
	Mg	See	
	Na	Figure 5	Rayment and Higginson (1992)
	K		
	Al		
	ECEC	derived	
	ESP	derived	

X-ray fluorescence analysis

Selected soil samples were assessed using X-ray fluorescence analysis. Major elements (Si, Ti, Al, Fe, Mn, Mg, K and Zr) were determined on a Philips PW 1480 X-Ray Spectrometer using lithium borate fusion discs. Fusion discs (1:9 dilution) were prepared with 12-22 flux (lithium tetraborate-lithium metaborate) and 0.5 g sample. All samples were powdered using a tungsten carbide mill. Corrections for mass absorption were calculated using Philips X40 software with De Jongh's calibration model and Philips (or CSIRO) alpha coefficients. Compton scattering was also used. Analyses were conducted at the School of Earth Sciences, University of Tasmania.

Principal component analysis

Penetration resistance and root distribution data sets were kriged using Surfer (v8.01) to provided gridded data points. Multivariate analysis was then undertaken on the interpolated values in JMP v8.0.

Presentation of soil data

Soil chemical data should be presented as step graphs, as this gives a true representation of the soil analysis due to the horizon based sampling method. However, this method of data presentation becomes impractical when comparing multiple datasets on the one graph. For this reason, graphs that compare datasets have been simplified by using the mid-horizon depth.

4. Vine growth and yield on soils formed on Tertiary Sediments

Introduction

In Tasmania, Tertiary Sediments were deposited into tectonic grabens or fault bound valleys formed as the New Zealand subcontinent moved eastward 60 – 50 Ma BP (Seymour *et al*, 2007). These deposits are typically fine textured but include a range of materials including sand, clay and gravel deposits. They are found in many valleys in Tasmania including the Coal, Huon, Derwent and Tamar Valleys. All of these areas are now being developed as separate wine regions. The Tamar Ridge Estates 'Kayena' vineyard has been established almost exclusively on these Tertiary Deposits. At approximately 150 ha, this vineyard is not only one of the largest in the Tamar Valley Wine Region, but also the second largest in Tasmania. The main reason for selecting sites on Tertiary Sediments is the low land purchase cost and the perception that soil constraints are secondary to climatic constraints and can be ameliorated with appropriate management such as drainage, fertilisers and irrigation.

The key soils formed from Tertiary Sediments are texture-contrast profiles with sandy loam topsoils over clayey subsoils. These particular texture-contrast soils are acidic and are classified as either Chromosols (slightly acid) or Kurosols (strongly acid). The principle soil constraints to production are the poor internal drainage, salinity, aluminium toxicity and other acidic soil conditions resulting in reduced uptake and utilisation of many other nutrients including phosphorous, calcium and magnesium.

General site description

Location

Both study sites were established at Tamar Ridge Estate's Kayena Vineyard. This vineyard is located in the Tamar Valley Wine Region in northern Tasmania (41°11' S, 146°53' E).

Geology and topography

The vineyard was mostly underlain by Tertiary sediments which include sand and gravel beds but are dominated by clay rich layers (Gee and Legge, 1971). The south-western boundary borders a low ridge which runs north-west to south-east and is capped by Jurassic dolerite. The contact between the dolerite and the Tertiary sediments is indicated to the north of the study area, however it has been marked as an inferred boundary indicating that it is an approximate location based on aerial photograph interpretation.

Existing soil maps

The study site is within the Beaconsfield-George Town reconnaissance soil map (Spandwick and Kidd, 2001) as shown in Figure 6. According to Spandwick and Kidd (2001) both the study sites are located within the Legana Soil Association that have developed from Tertiary sands, clays and gravels (Figure 6). The main soil orders in this mapped soil association are Chromosols, Kurosols and Podosols. To the south of the Pinot Noir block are soils mapped as the Ecclestone Soil Association in which soils have developed from lateritised Jurassic dolerite, Tertiary sediments and Jurassic dolerite. The main soil orders found in the Ecclestone Soil Association are Ferrosols, Sodosols and Chromosols. The boundary between these map units is inferred (dashed line) indicating that this has not been field checked and has been based on aerial photographic interpretation.

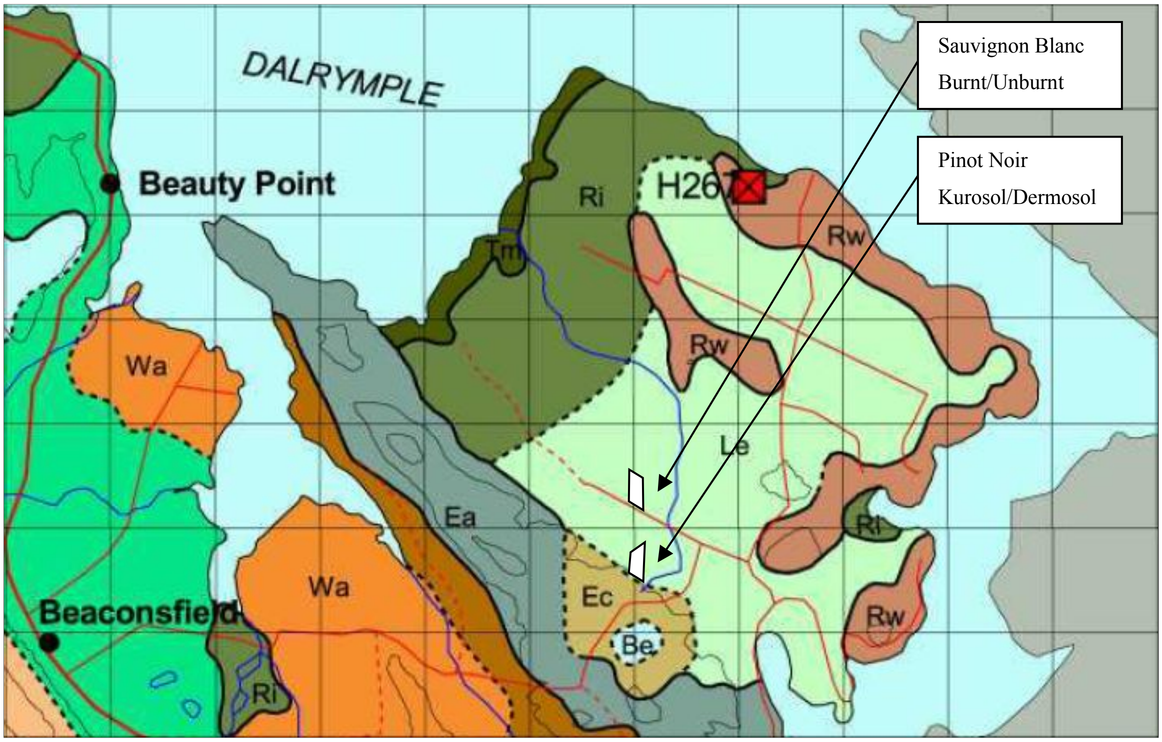

Figure 6: 1:100 000 soil map of the region (Spandwick and Kidd, 2001). Approximate locations of the studied sites are shown. Grid lines signify intervals of 1 km.

	Map Symbol	Map Unit	Map Unit Concept	Australian Soil Classification	Great Soil Group (dominant soils)
Soils developed on hard rocks					
	Ea	Eastfield Association	Imperfectly drained texture contrast soils developed from Jurassic dolerite on rugged hilly land with frequent rock outcrops.	Chromosols	Grey-brown Podzolic
	Wa	Warrina Association	Soils developed from Permian mudstone, siltstone on very gently undulating to rolling or hilly land below 150m.	Kurosols	Yellow Podzolics
Soils on unconsolidated materials					
	Le	Legana Association	Soils developed from Tertiary sands, clays and gravels on gently rolling to rolling land.	Chromosols, Kurosols & Podosols	Yellow Podzolics, Lateritic Podzolics and Podzols
	Be	Beconsfield Association	Soils developed from late Tertiary quartz sands and gravels on undulating surfaces. Much white angular quartz gravel on surface.	Podosols	Podzols
	Ri	Robigana Association	Soils developed from Pleistocence and recent marine sediments on marine benches. Some superimposed low sand dunes in places.	Podosols	Podzols, black clays, saline soils, shallow brown soils
	Tm	Tamar Association	Soils developed from recent estuarine deposits on low-lying waterlogged flats.	Hydrosols	Fine textured saline gleyed soils
Soils on a mixture of unconsolidated sediments & hard rock					
	Ec	Ecclestone Association	Soils developed from lateritized Jurassic dolerite, Tertiary ferruginous sediments and Jurassic dolerite on rolling to hilly land with some rock outcrops.	Ferrosols, Sodosols &/or Chromosols	Lateritic Krasnozems, Lateritic Podzolic soils and Grey-brown Podzolic soils
	Rw	Rosevears Association	Soils developed from mixed Tertiary clays and basalt on rolling to hilly land with frequent slump benches and some steep rocky scarps.	Chromosols, Ferrosols & Dermosols	Yellow Podzolics, Krasnozems and shallow brown soils

Individual site layout

The two study sites were selected that represented both high and low vigour levels within a small area. These were identified by Wells (2011) using aerial infrared imaging. The vines were measured over three years, commencing in the 2005-06 season. All trials were drip irrigated and all vines were own-rooted. All vineyard blocks had rows in a north-south orientation with row and vine spacing of 2.25 m and 1.5 m respectively. All vines received similar management within each vineyard block and were harvested on the same day each year.

One site was within a block of Pinot Noir (clone G5V15). This site was selected to investigate vine growth on contrasting soil types (Kurosol compared to a Dermosol). This vineyard block was cane pruned on a Scott Henry trellis.

The second site was within a block of Sauvignon Blanc (clone unknown) where the clearing of native vegetation had resulted in two distinct soil conditions; areas of scalped/reduced topsoil thickness compared to conspicuous zones of over thickened and burnt topsoils. This vineyard block was cane pruned to 40 buds on a vertical shoot positioned (VSP) trellis.

Climate background at site

Monthly rainfall was determined using data obtained from the Bureau of Meteorology weather station situated at Beconsfield (station number 091001), 12 km to the west of the vineyard. The mean annual rainfall for the region was 944 mm with typically a winter dominant pattern. During the 2005-06 season, rainfall was above average with a large amount of late winter rain (Figure 7). Rainfall during both 2006-07 and 2007-08 were below average, particularly during the growing season.

The average monthly temperature was recorded by the Bureau of Meteorology weather station situated at Low Head (station number 091293), 10 km north of the vineyard. The average maximum monthly temperature is shown in Figure 8, and shows that temperatures were consistent between the studied years. The average monthly temperature was slightly above the long-term average in all years (Table 6).

Table 6: Annual rainfall and average monthly temperature. Rainfall average from Beconsfield (station number 091011) from 1901 – 2011. Temperature average from Low Head (station number 091293) from 1997 – 2010.

Season	Rainfall (mm)	Temperature (^{o}C)
2005-06	1041	16.4
2006-07	500	16.8
2007-08	787	16.2
Long-term average	944	16.1

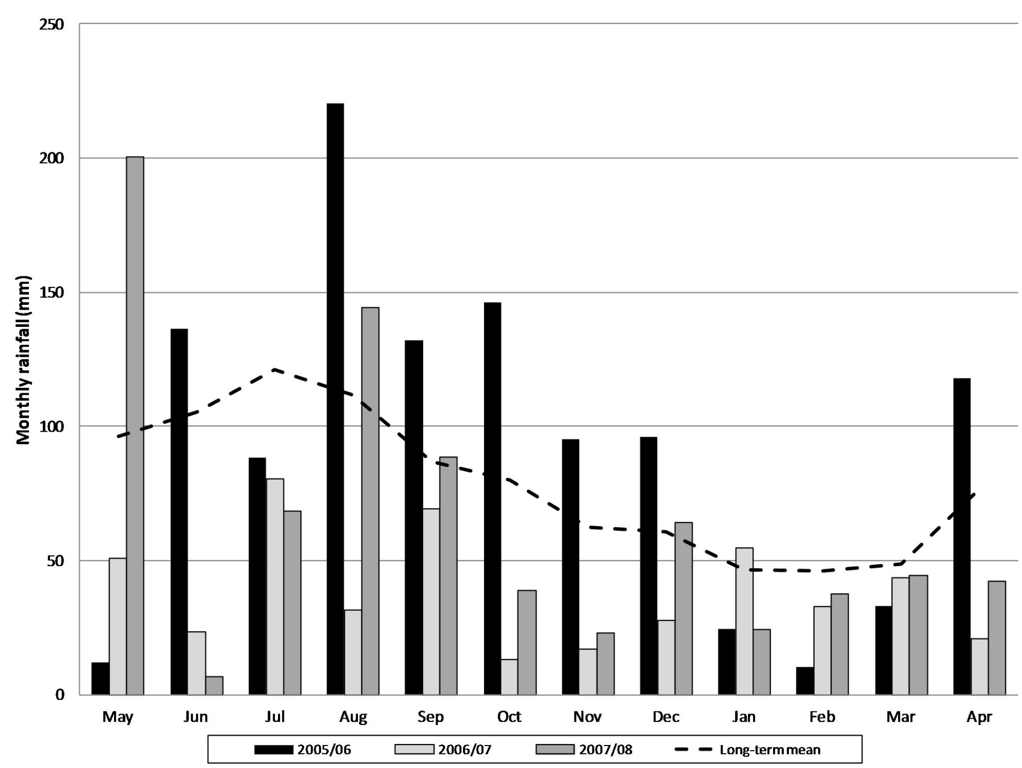

Figure 7: Monthly rainfall (Low Head, station number 091293)

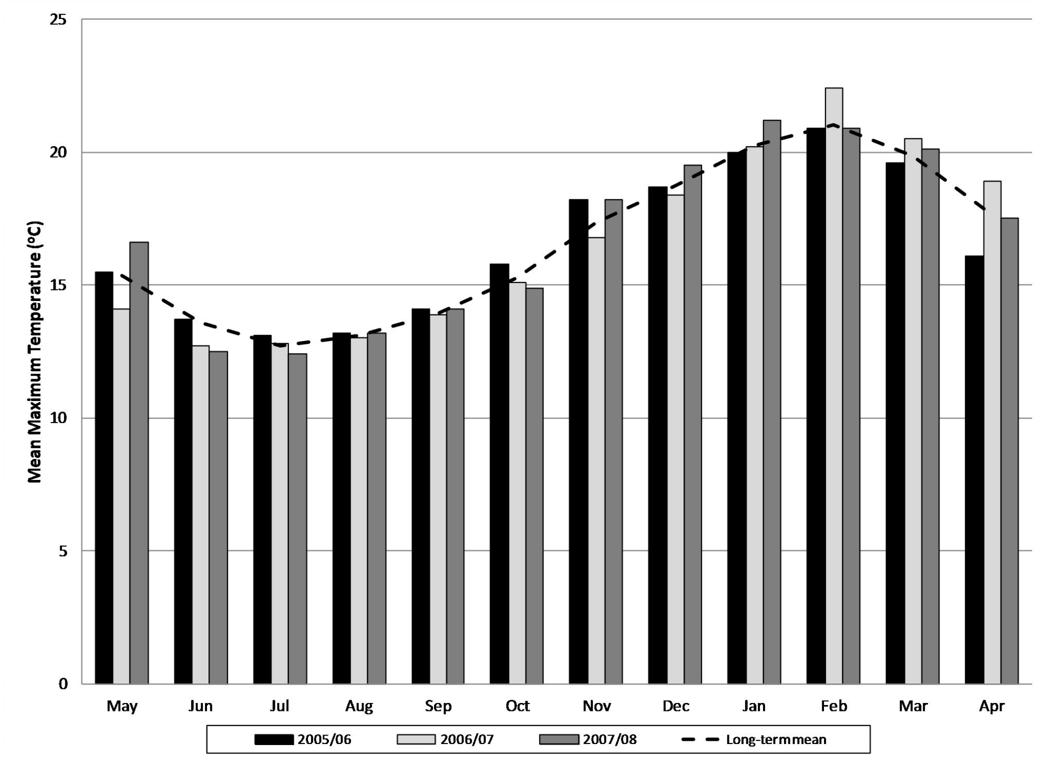

Figure 8: Mean monthly maximum temperature (Beaconsfield, station number 091001)

Results

Remote sensing

The aerial vigour map of the Pinot Noir block shows that the plant cell density (PCD) varied across the vineyard block (Figure 9a). The block mainly had low PCD values (red/yellow) with both the northern and southern boundaries having higher PCD values (green/blue). This signifies that these areas had higher vigour than the rest of the vineyard block. The Dermosol soil profile was located within distinctly higher PCD values at the south-eastern corner of the block. The Kurosol profile was positioned within a region of low PCD values and represents the vigour for the majority of the vineyard block. The EM38 survey showed that bulk electrical conductance varied across this vineyard block (Figure 9b). The Dermosol profile was within an area of low apparent electrical conductivity (ECa) and the Kurosol profile within an area of high ECa. As ECa is dependent of many potential soil attributes, this map indicates that the Kurosol had either higher soil salinity, higher soil moisture, higher proportion of clay and/or shallower depth to clay than at the Dermosol profile.

Most of the Sauvignon Blanc block had low PCD values (Figure 10a). Distinct zones of higher PCD values are clearly observed (green) and relate to the areas of windrowing and burning that occurred during prior land clearing and site establishment. The Kurosol-Burnt profile was located within a region of highest PCD, located towards the southern end of the vineyard block. The Kurosol-Scalped profile was located outside this region and within low PCD values. The EM38 survey demonstrate most of the soil within the vineyard block had low ECa. In contrast, the burnt areas showed high ECa present due to higher conductance suggesting either; higher moisture content, higher soil salinity and/or higher clay content.

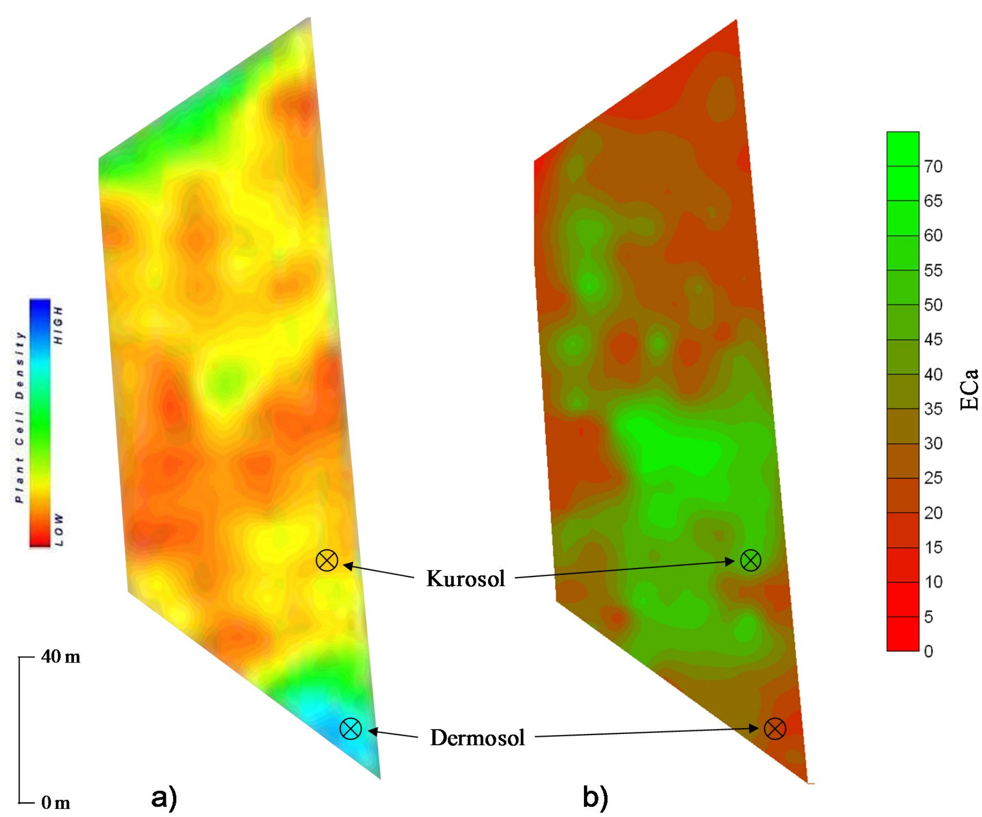

Figure 9: Remote sensing of the Pinot Noir study area showing a) the infra-red image of plant cell density; and b) EM38 soil survey (vertical dipole). The locations of the examined soils are marked.

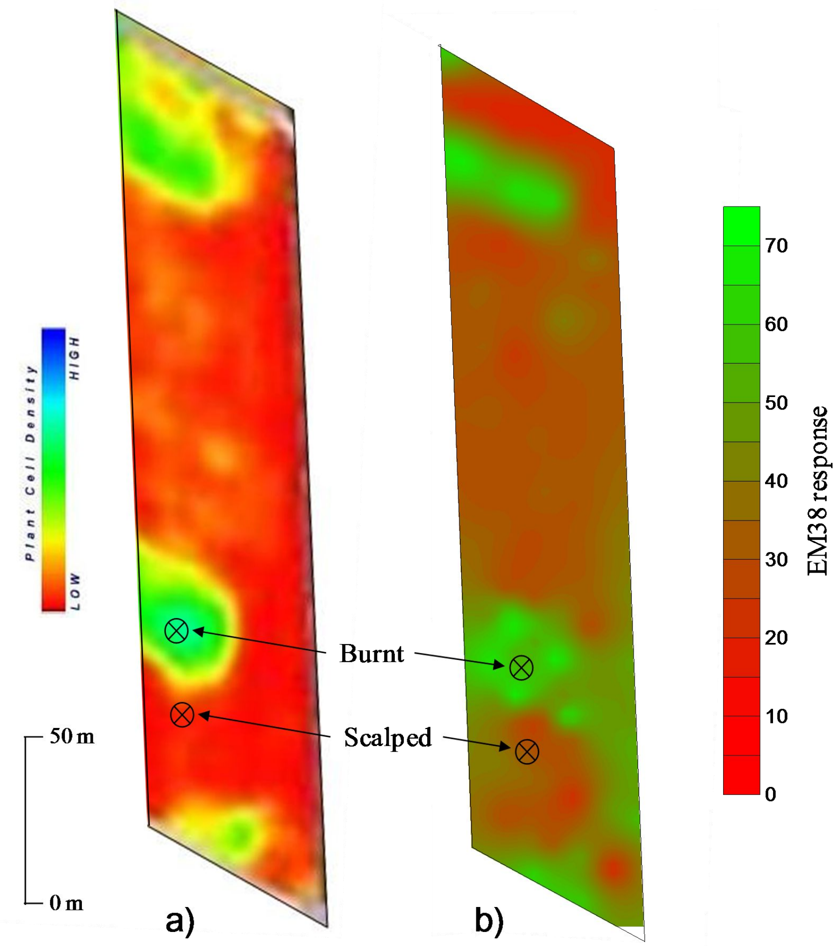

Figure 10 Remote sensing of the Sauvignon Blanc study area. showing a) the infra-red image of plant cell density; and b) EM38 soil survey (vertical dipole). The locations of the examined soils are marked; 'Burnt' representing Kurosol-Burnt and 'Scapled representing Kurosol-Scalped.

Table 7: Soil Classification summary

Soil Profile	Order	Suborder	Great Group	Subgroup	Family criteria					
					A horizon thickness	Gravel (surface and A1)	A1 Horizon texture	B horizon maximum texture*	Soil depth	Slope angle (%)
Kurosol-Burnt	KU	AB	AH	AZ	C	F	L	O	X	1
Kurosol-Scalped	KU	AB	AH	AZ	B-A	F	L	O	X	1
Kurosol	KU	AB	FD	HB	B	F	L	O	X	4
Dermosol	DE	AB	AH	EO	B	F	L	O	X	6

*estimated from field texture

Key to Classification codes:

AB – Brown

AH – Eutrophic

AZ – Bleached-Mottled

EO – Sodic

FD - Natric

HB – Mottled-Sodic

KU – Kurosol

DE - Dermosol

A – Thin (< 0.1 m)

B – Medium (0.1 – 0.3 m)

C – Thick (0.3 – 0.6 m)

F - Slightly gravelly (2 – 10 %)

L – Loamy (SL-L, 10 – 20 % clay)

O – Clayey (LC-MC-HC, > 35 % clay)

X –Deep (1.5 – 5 m)

Summary soil descriptions

Both the Kurosol-Burnt and Kurosol-Scalped profiles at the Sauvignon Blanc site were formed on Tertiary sediments and classified as Bleached-mottled, Eutrophic, Brown Kurosols (Isbell, 1996). Both profiles consisted of texture-contrast profiles with pale sandy topsoils overlying mottled clayey subsoils (Figure 11). The subsoils had weak to moderately developed coarse columnar structure with many sand filled cracks. The overall similarity of these profiles led to almost identical soil classifications (Table 7) with the only difference occurring at the family level due to a discrepancy in topsoil thickness. The thickness of the topsoil had been reduced due to scalping from the unburnt areas with resulting accumulation of over thickened topsoil in the burnt zone. Topsoil thickness therefore varied from greater than 40 cm at Kurosol-Burnt profile to less than 10 cm in the Kurosol-Scalped profile. The result of burning had meant that charcoal was present throughout the topsoil of the Kurosol-Burnt profile, with occasional areas of high concentrations. The topsoil showed signs of soil mixing and obvious site disturbance.

The Kurosol-Sodic profile at the Pinot Noir site was also formed from Tertiary Sediments (sand and clay). This soil profile consisted of a greyish brown sandy topsoil overlying a grey and orange mottled clayey subsoil that was somewhat similar to both the Sauvignon Blanc profiles (Figure 12) however the lack of a conspicuously bleached A2 horizon resulted in this soil being classified as a Mottled-Sodic, Natric, Brown Kurosol (Isbell, 1996). The mottled subsoil is shown in Figure 14b, and indicates that this material has undergone repeated oxidised/reduced conditions. Decaying roots were also prominent throughout the subsoil. These roots were remnants from previous woodland vegetation and had varying degrees of decomposition. The softer and organic rich nature of these decaying roots allowed preferential growth of vine roots to occur in these areas (Figure 14a). Gleyed colours were often present immediately below these areas (Figure 14a) indicating that water movement through these decaying channels becomes impeded by the underlying soil. This contrasts with the grey and orange mottling of the surrounding sediments.

At the time of excavation, water was observed flowing from within the B21 (at 40 cm). The electrical conductivity (EC) of this water was measured at 5 dS/m. The flow volume was sufficient to fill the soil trench with water within 14 hours (overnight) (Figure 14d). This demonstrates that a shallow saline watertable was present in this profile. It is expected that the depth and salinity of this watertable would fluctuate seasonally.

The Dermosol profile mainly consisted of a brown clay loam topsoil formed from what was interpreted as dolerite colluvium. This overlay a mottled clayey subsoil formed from Tertiary sediments which was similar to the subsoil observed at the Kurosol-Sodic profile. An indistinct stone-line was evident at 60 cm separating the two materials. Water was also observed seeping from the subsoil of this profile at a depth of 100 cm (within the 2B23b). The EC of this water was measured at 2 dS/m.

Figure 11: Sauvignon Blanc soil profiles showing a) Kurosol-Burnt profile with deeper darker topsoil horizons; and b) Kurosol-Scalped profile with shallow topsoil.

Figure 12: Pinot Noir Kurosol-Sodic profile. The dark colourations within the subsoil indicate decaying old roots of previous vegetation species.

Figure 13: Pinot Noir Dermosol profile. The upper 60 cm of the profile was determined to have been derived from dolerite colluvium with the lower horizons derived from Tertiary sediments. The location of a faint stone-line is marked (arrow)

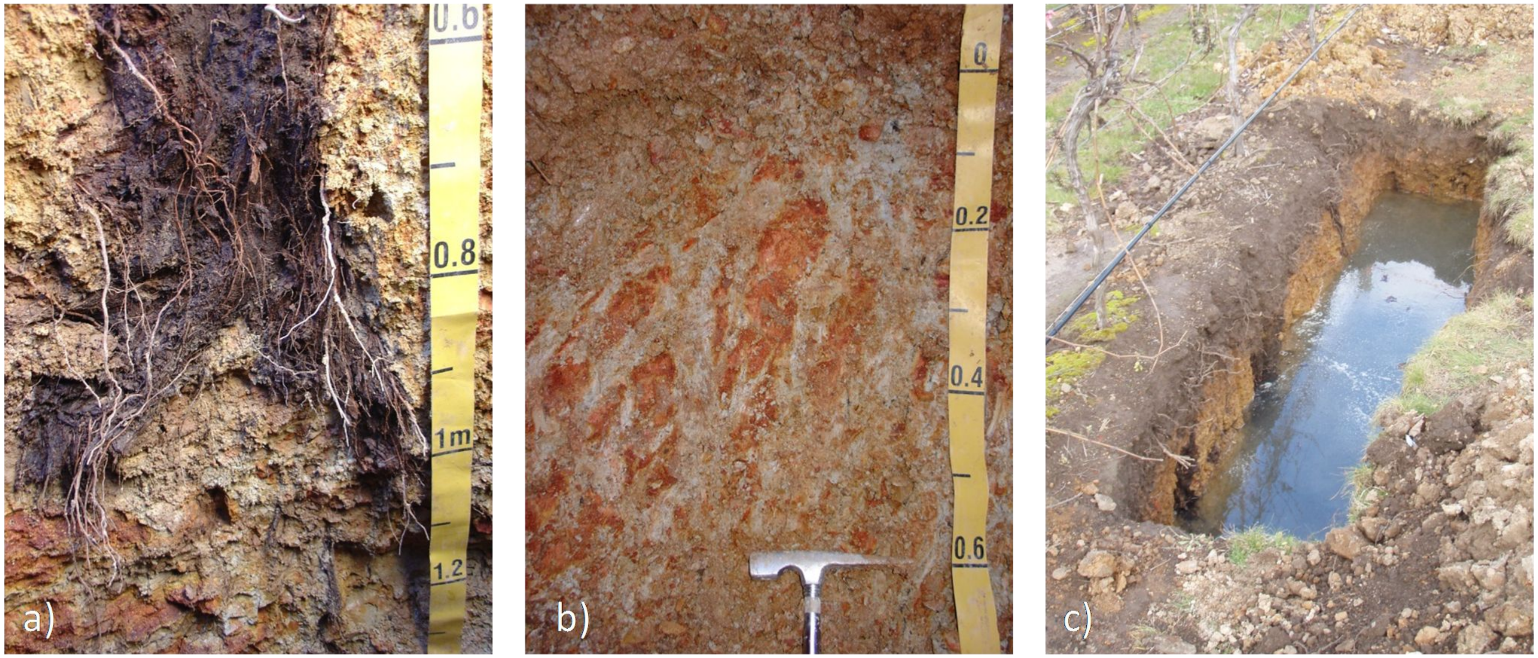

Figure 14: Special features of the Kurosol profile showing a) Preferential root growth constrained within an old decomposed tap root; b) examples of mottling seen in the Tertiary sediments at the base of the pit; c) presence of a shallow watertable (saline); and d) close up of a vine root preferentially growing through a root from previous vegetation.

Table 8: Summary of key profile features

Horizon	Depth (cm)	Matrix Colour (moist)			Texture	Structure							Consistence
						Primary				Secondary			
Kurosol-Burnt													
A11	0 – 20	10YR	4	1	SL-	W	f	PO	+	W	m-f	PO	Weak
A12	20 – 40	10YR	4	1	SL	W	m-f	PO	+	W	f	PO	Weak
A2	40 – 58	10YR	6	2	S			SG					Firm
B21	58 – 90	10YR	5	6	LMC	M	c	CO					Firm
B22	90 – 115	10YR	5	6	LMC	M	c	PR					Firm to very firm
B23	115-135+	2.5Y	6	3	LMC	W	c	PR					Strong
Kurosol-Scalped													
A11	0 – 10	10YR	4	1	SL	W	f	PO	+	W	m-f	PO	
A12	10 – 26	10YR	4	1	SL	W	m-f	PO	+	W	f	PO	
A2	26 – 36	10YR	6	2	S			SG					
B21	36 – 60	10YR	5	6	LMC	M	c	CO					Firm
B22	60 – 85	10YR	5	6	LMC	M	c	PR					Firm to very firm
B23	85 - 115	2.5Y	6	3	LMC	M	c	PR					Strong
B24	115-140+	2.5Y	6	2	LMC	W	c	PR					Strong
Kurosol -Sodic													
A11p	0 – 10	10YR	2	1	SL	W	f	PO	+	W	m	PO	Weak
A12	10 – 22	10YR	3	3	SL	W	m-f	PO	+	W	f	PO	Weak
B21	22 – 41	10YR	4	4	LC	W	m	PO					Firm
B22	41 – 60	10YR	4	4	LMC	W	m	PO					Firm
B23	60 – 95	10YR	5	6	LMC	W	m-c	PO					Firm
B24	95 - 130+	2.5Y	6	3	LMC	W	m-c	PO					Firm to very firm
Dermosol													
A11p	0 – 7	10YR	3	3	SCL	S	m-f	PO	+	S	f	PO	
A12	7 – 18	10YR	3	3	SCL	S	m-f	AB	->	M	f	AB	
A3	18 – 28	7.5YR	4	4	CL	M	m-f	AB	->	W	f	AB	
B21	28 – 55	5YR	4	6	LC	W	m	AB					Firm
2B22b	60 – 95	10YR	5	6	LMC	W	m	PO					Firm
2B23b	95-120	10YR	5	6	LMC	W	m-c	PO					Firm
2B24b	120-135+	2.5Y	6	3	LMC	W	m-c	PO					Firm to very firm

See Appendix 1 for a description of codes

Soil profile chemical analysis

Soil chemical attributes of the four soil profiles are presented in Table 9 and Figure 15. The soil chemistry of all the Kurosol profiles was dominated by an acidic reaction trend in which all profiles had strongly acid subsoils ($pH_w < 5.5$, $pH_{CaCl_2} < 4.6$). Slight differences of pH occurred below 60 cm, with the Kurosol-Scalped soil having higher values by up to 0.5 of a unit. The greatest differences in soil chemistry generally occurred in the upper profile (0 - 40 cm). The Kurosol-Scalped topsoil had substantially lower levels of organic carbon, exchangeable Ca^{2+}, exchangeable Mg^{2+}, exchangeable K^+ and ECEC than the other Kurosol profiles. These values were approximately 1.5 – 2 times less than the corresponding depths of the Kurosol-Scalped soil. Little difference in chemical attributes of the Kurosol profiles existed below 50 cm depth. The only exceptions were higher electrical conductivity and exchangeable Na^+ within the Kurosol-Sodic profile and the substantially higher exchangeable Al^{3+} within the Kurosol-Burnt profile. This difference in aluminium relate to the lower pH that also occurred throughout this profile. The high sodium values of the Kurosol-Sodic profile were reflected in high exchangeable sodium percentage (ESP) values throughout the profile, ranging from 9.2 % within the topsoil to over 30 % within the subsoil. Consequently every horizon was classed as sodic (ESP > 6 %) with the subsoil horizons being strongly sodic (ESP > 15 %). The only other Kurosol to have sodic horizons was the Kurosol-Scalped profile that had an ESP of 6.9 % at depths below 115 cm.

The Dermosol profile had relatively consistent pH throughout the profile ranging from 6.4 in the topsoil to 5.6 within the subsoil (pH_{CaCl_2}). Organic carbon levels were high in the topsoil, as was the ECEC and most exchangeable base cations (Ca^{2+}, Mg^{2+} and K^+). These values were higher than both the Kurosol-Scalped and Kurosol-Sodic topsoils but were generally similar to topsoil values at the Kurosol-Burnt profile. Exchangeable Na^+ was low within the topsoil, but increased with depth and horizons below 45 cm were classed as strongly sodic (ESP > 15 %). Below 60 cm, the Dermosol had lower exchangeable Mg^{2+} than all Kurosol profiles and no exchangeable Al^{3+} was detected throughout the entire Dermosol profile, yet it had higher XRF Al_2O_3 than the Kurosol-Sodic profile. The whole soil XRF analysis (Table 10) showed clear chemical differences between the Dermosol and Kurosol-Sodic profiles and highlights that the upper 55 cm of the Dermosol (above the stone-line) has been formed from separate parent material, interpreted as dolerite colluvium. The Dermosol profile had higher Al_2O_3 and Fe_2O_3 throughout the upper horizons (0 – 55 cm) than the Kurosol-Sodic profile. The upper profile of the Dermosol also had substantially less SiO_2 indicating less silica sand component supported by heavier soil texture within the topsoil than at the Kurosol-Sodic profile. The higher Al_2O_3 and Fe_2O_3 and lower SiO_2 within the upper profile of the Dermosol is consistent with data of soils formed from dolerite and dolerite colluvium (Osok and Doyle, 2004; Nicolls, 1958; Leaman, 2000).

Table 9: Selected soil chemistry analysis.

Horizon	Depth (cm)	pH (1:5) CaCl$_2$	H$_2$O	EC (dS/m)	Exchangeable Cations (cmol(+)/kg) Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Al^{3+}	ECEC	ESP (%)	Org C (%)
Kurosol-Burnt												
A11	0 – 20	6.3	7	0.12	16.7	7.3	0.2	1.6	0.0	25.8	0.8	4.1
A12	20 – 40	4.8	5.5	0.13	6.7	2.3	0.2	0.2	0.3	9.9	2.2	3.5
B1	40 – 58	4.7	5.6	0.04	2.3	1.1	0.1	0.2	0.6	4.3	3.3	2.1
B21	58 – 90	4.2	5	0.07	2.6	6.6	0.3	0.3	1.6	11.5	2.7	0.5
B22	90 – 115	4.2	4.8	0.08	2.2	7.7	0.5	0.2	1.9	12.4	3.7	0.4
B23	115 – 135+	4.1	4.9	0.08	1.8	9.3	0.5	0.2	2.0	13.8	3.9	0.3
Kurosol-Scalped												
A11	0 – 10	6.9	7.5	0.09	6.9	2.1	0.1	0.5	0.0	9.5	1.2	1.5
A12	10 – 26	6.4	7.1	0.06	6.2	2.0	0.2	0.2	0.0	8.6	1.8	1.5
A2	26 – 36	4.9	5.7	0.07	1.4	1.0	0.1	0.1	0.2	2.9	3.5	0.7
B21	36 – 60	4.8	5.4	0.05	2.3	3.3	0.2	0.2	0.2	6.2	3.1	0.5
B22	60 – 85	4.8	5.5	0.06	2.3	7.5	0.4	0.2	0.2	10.5	3.7	0.3
B23	85 – 115	4.7	5.4	0.06	1.6	10.8	0.7	0.2	0.3	13.6	5.4	0.3
B24	115 – 140+	4.4	5.0	0.08	1.1	10.6	0.9	0.1	0.7	13.5	6.9	0.2
Kurosol-Sodic												
A11	0 – 10	6.2	7.1	0.18	15.9	3.4	2.1	1.2	0.0	22.6	9.2	4.0
A12	10 – 22	5.8	6.6	0.24	10.4	3.8	2.1	0.5	0.0	16.8	12.6	3.9
B21	22 – 41	5.3	6.1	0.11	3.3	3.6	2.2	0.2	0.1	9.4	23.0	1.5
B22	41 – 60	4.8	5.3	0.25	1.1	3.3	2.2	0.1	0.3	6.9	31.4	0.7
B23	60 – 95	4.9	5.5	0.39	0.9	8.5	2.9	0.1	0.2	12.6	23.3	0.5
B24	95 – 130+	4.7	5.2	0.45	0.6	8.9	3.5	0.1	0.2	13.2	26.2	0.2
Dermosol												
A11	0 – 7	6.4	7.1	0.17	17.3	7.9	0.3	1.6	0.0	27.2	1.2	3.8
A12	7 – 18	6.1	6.8	0.12	12.0	7.1	0.2	1.6	0.0	20.9	1.1	3.5
A3	18 – 28	5.6	6.4	0.09	3.8	2.8	0.4	1.0	0.0	8.0	4.9	1.4
B21	28 – 55	5.9	6.5	0.16	2.1	4.1	1.3	0.2	0.0	7.6	16.5	0.5
2B22b	60 – 95*	6.0	6.5	0.18	1.7	4.0	1.3	0.2	0.0	7.1	18.1	0.3
2B23b	95 – 120	5.6	6.2	0.02	1.9	5.1	1.8	0.1	0.0	8.9	20.3	0.3
2B24b	120 – 135+	5.7	6.1	0.30	1.9	5.2	2.1	0.1	0.0	9.3	22.6	0.2

* the inconsistent depth between the B21 and 2B22b indicates the presence of a stoneline

Table 10: Selected XRF elements of the Pinot Noir profiles.

Horizon	Depth (cm)	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	Na_2O	K_2O	Zr
Kurosol-Sodic									
A11	0 – 10	-	-	-	-	-	-	-	-
A12	10 – 22	70.41	2.82	8.90	6.21	0.21	0.26	0.36	0.11
B21	22 – 42	49.39	2.55	11.68	7.20	0.16	0.26	0.08	0.06
B22	42 – 60	49.34	2.38	16.19	6.52	0.13	0.27	0.03	0.10
B23	60 – 95	-	-	-	-	-	-	-	-
B24	95 – 130+	40.02	1.39	35.64	3.57	0.01	0.29	< 0.01	0.09
Dermosol									
A11	0 – 7	-	-	-	-	-	-	-	-
A12	7 – 18	51.04	2.89	18.31	7.09	0.35	0.29	0.39	0.05
A3	18 – 28	45.27	2.45	22.39	14.18	0.19	0.25	0.09	0.03
B21	28 – 55	41.17	1.98	27.74	12.62	0.08	0.31	0.04	0.05
2B22b	60 – 95*	35.29	1.85	31.88	11.40	0.04	0.27	0.03	0.04
2B23b	95 – 120	-	-	-	-	-	-	-	-
2B24b	120 – 135+	33.87	0.94	38.99	4.73	0.02	0.31	0.03	0.06

* the inconsistent depth between the B21 and 2B22b indicates the presence of a stoneline which separates two types of parent material

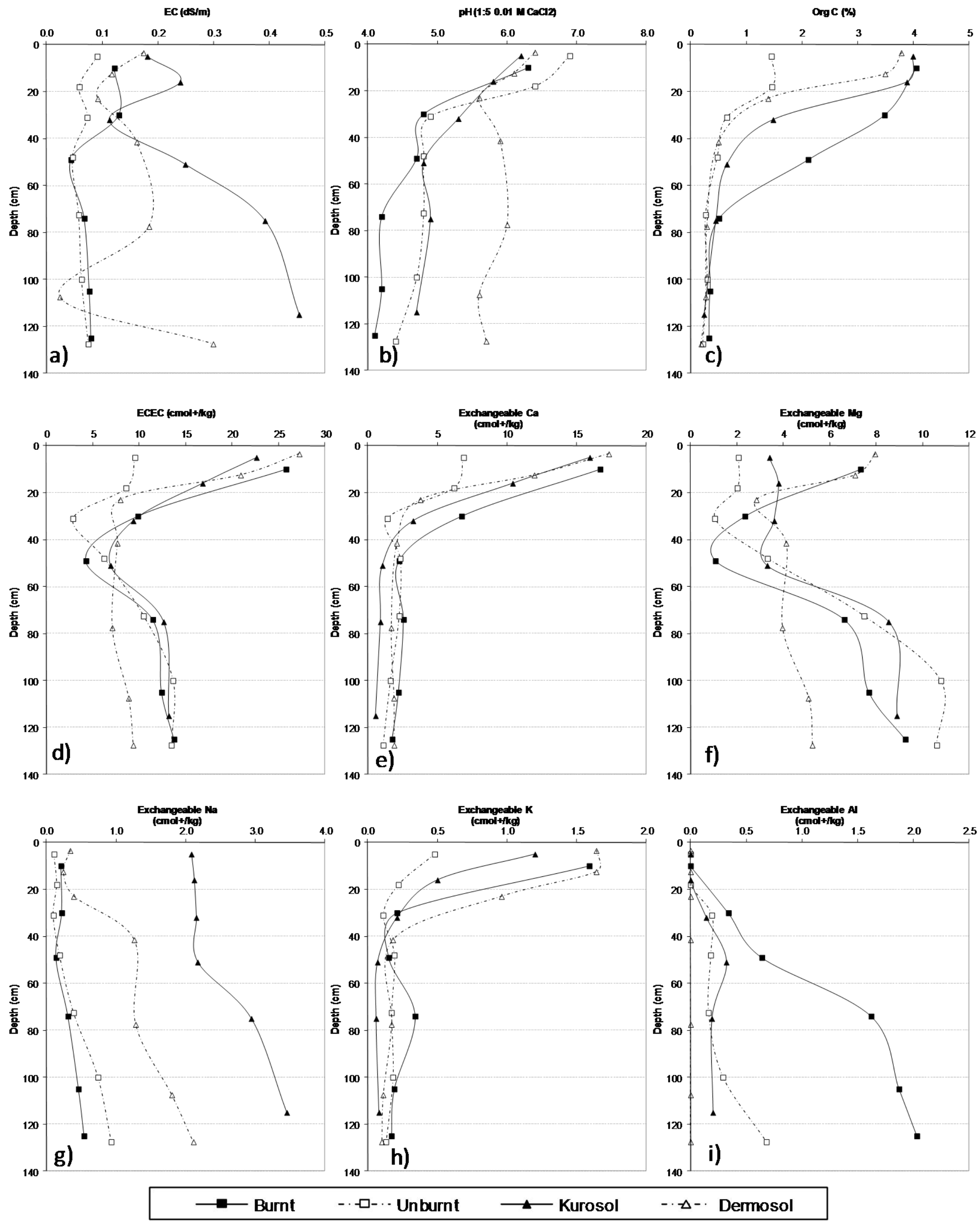

Figure 15: Combined soil chemistry of the profiles at Tamar Ridge Estate. Similarities can be seen between all the texture-contrast profiles (Kurosol-Burnt, Kurosol-Scalped & Kurosol-Sodic) particularly within subsoil horizons.

Soil penetration resistance

Penetration resistance values within the topsoil were generally low (< 1 MPa) and similar between all profiles. Increasing penetration resistance values were recorded with depth at Kurosol-Burnt and Kurosol-Scalped profiles (Figure 16a & b) with both commonly having penetration resistance values between 1.5 – 2 MPa, exceeding 2.5 MPa at the bottom of both profiles. The Kurosol-Scalped profile had higher MPa values at shallower depths than the other profiles reflecting the thinner topsoil at this site. This was particularly evident on the right-hand side of the profile, where most of the subsoil had > 2 MPa below 55 cm. Within both profiles, vertical banding of penetration resistance data can be observed at both Sauvignon Blanc profiles. Here zones of lower penetration resistance occurred where subsoil cracks were in-filled with sandier topsoil material. The measured MPa was generally 0.5 – 1 MPa lower in these regions than the rest of the subsoil. Examples of these in-filled cracks are shown in Figure 19.

At the Pinot Noir site, both profiles had lower MPa values within the subsoil than those at the Sauvignon Blanc site. These were commonly 1 – 1.5 MPa and only exceeded 2 MPa in isolated regions. The presence of decaying old roots within the Kurosol-Sodic subsoil (e.g. Figure 14a) also resulted in localised regions of low MPa values (< 1 MPa).

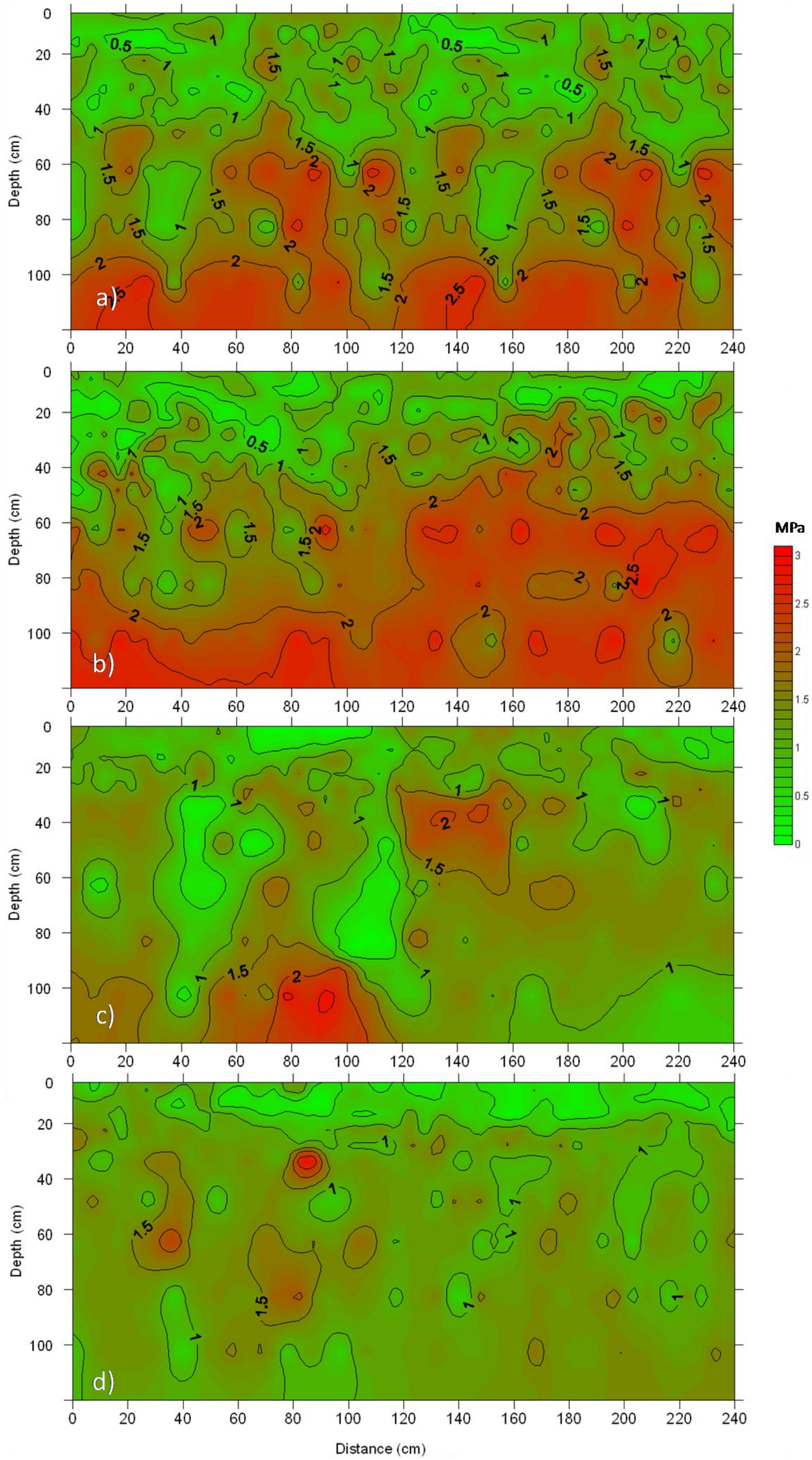

Figure 16: Soil penetration resistance. Soil profiles are a) Kurosol-Burnt; b) Kurosol-Scalped; c) Kurosol-Sodic; and d) Dermosol. Vertical bands of lower resistance values can be seen within the subsoil of (a) & (b) and reflect cracks and areas of sand in-fill. Decaying old roots have caused the large areas of lower penetration resistance within (d) .

Root Distribution

Differences in root distribution were observed across the exposed face of the examined profiles (Figures 17 and 18). While all profiles had highest concentrations of roots in the topsoil, a considerable number of roots were also observed within subsoil horizons. Root distribution within the subsoils related strongly to soil structure and cracking patterns. The exception being the Kurosol-Scalped profile which had very limited subsoil root growth. This was most apparent with the distribution of fine roots (< 1 mm). At the Kurosol-Burnt profile, the subsoil distribution showed nearly vertical linear concentrations of fine roots. Figure 19 shows that these correspond to the location of sand filled cracks present within the subsoil. A similar relationship was observed at the Kurosol-Scalped profile however it was mostly observed on only one half the profile face (left-hand side), with limited root growth was observed within the subsoil on the right-hand side.

Substantially more roots were observed at the Kurosol-Burnt profile than the Kurosol-Scalped profile. Table 12 shows that the total root number was twice that of the Kurosol-Scalped profile (1867 total roots compared to 930). This difference was relatively consistent across all the root sizes with the Kurosol-Burnt profile having approximately double the roots in each respective size class. While the total number of roots differed between profiles, the percentage distribution of each size class was relatively similar. The fine roots (< 1 mm) were the dominant size class observed and accounted for 88.8 % and 86.6 % of the root observations (Kurosol-Burnt and Kurosol-Scalped profiles respectively). Both profiles had less than 10 % of the observations for the 1 – 2 mm root size class (7.2 % and 9.9 % respectively) with the remaining two classes making up the remaining 4 %.

At the Pinot Noir site, the total root numbers (Table 13) were relatively similar between the two profiles. Total root number was slightly higher for the Kurosol profile (1908 compared with 1591 within the Dermosol) with most of the difference due to a greater abundance of fine (< 1 mm) roots (1731 compared to 1421). While both profiles had similar root growth with depth (Figure 21), noticeable differences in root distribution existed laterally within the subsoil (Figure 18). Roots growing within the Kurosol were concentrated in distinct regions of the subsoil that corresponded with old areas of prior root growth (from previous forest vegetation). Figure 19 shows that all of the root growth within the subsoil of this profile corresponded to these regions, compared to only minor occurrences at the Dermosol profile.

Estimation of Plant Available Water

The estimated values of plant available water (PAW) using the upper 1 m of soil were similar, with only 10 mm/m difference occurring between all profiles (Table 11). However differences in PAW did occur when calculated using the effective rooting depth (90 % of root observations). Using this calculation the Dermosol profile had highest estimated PAW followed by the Kurosol-Burnt and Kurosol-Sodic profiles. The Kurosol-Scapled profile had the lowest estimated PAW within the effective rooting depth.

Table 11: Estimation of plant available water (PAW)

Profile	PAW (1 m depth) (mm/m)	Depth of 90% root observations (cm)	PAW (90 % roots) (mm)
Kurosol-Burnt	110.8	87.5	95.8
Kurosol-Scalped	114.7	60.0	66.7
Kurosol-Sodic	118.9	72.5	85.9
Dermosol	120.9	87.5	111.9

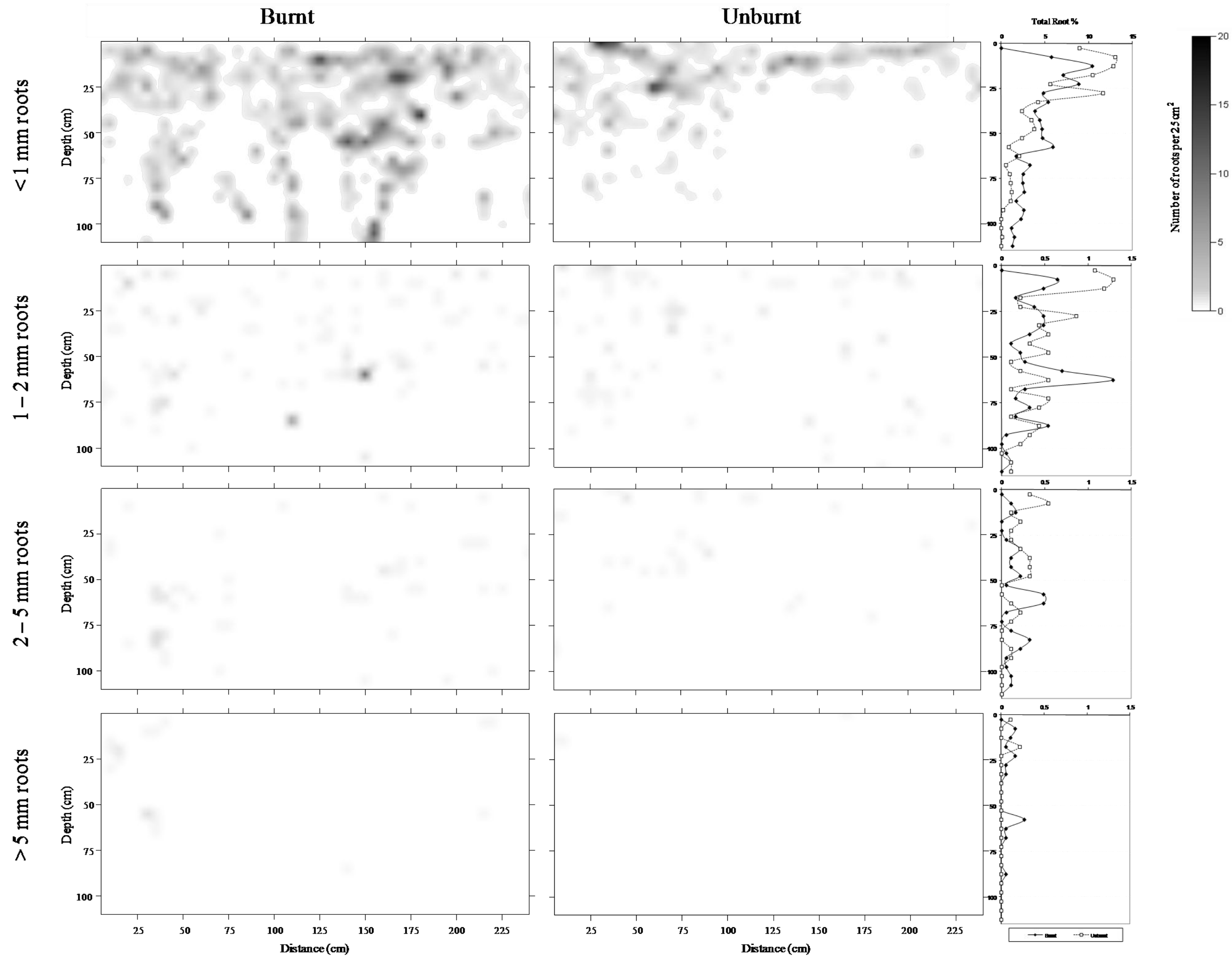

Figure 17: Sauvignon Blanc root distribution for the Kurosol-Burnt (left) and Kurosol-Scalped (right) profiles showing the distribution of the following diameter classes: a) < 1mm; b) 1 – 2 mm; c) 2 – 5 mm; d) > 5 mm. Darker shading indicates higher root density. The right-hand graph shows the percentage of total roots for each size class with depth. Note: the scale for < 1 mm root class is ten times greater than the other classes demonstrating the abundance of this root size class.

Root numbers with depth for different root size classes within the Kurosol-Burnt and Kurosol-Unburnt profiles

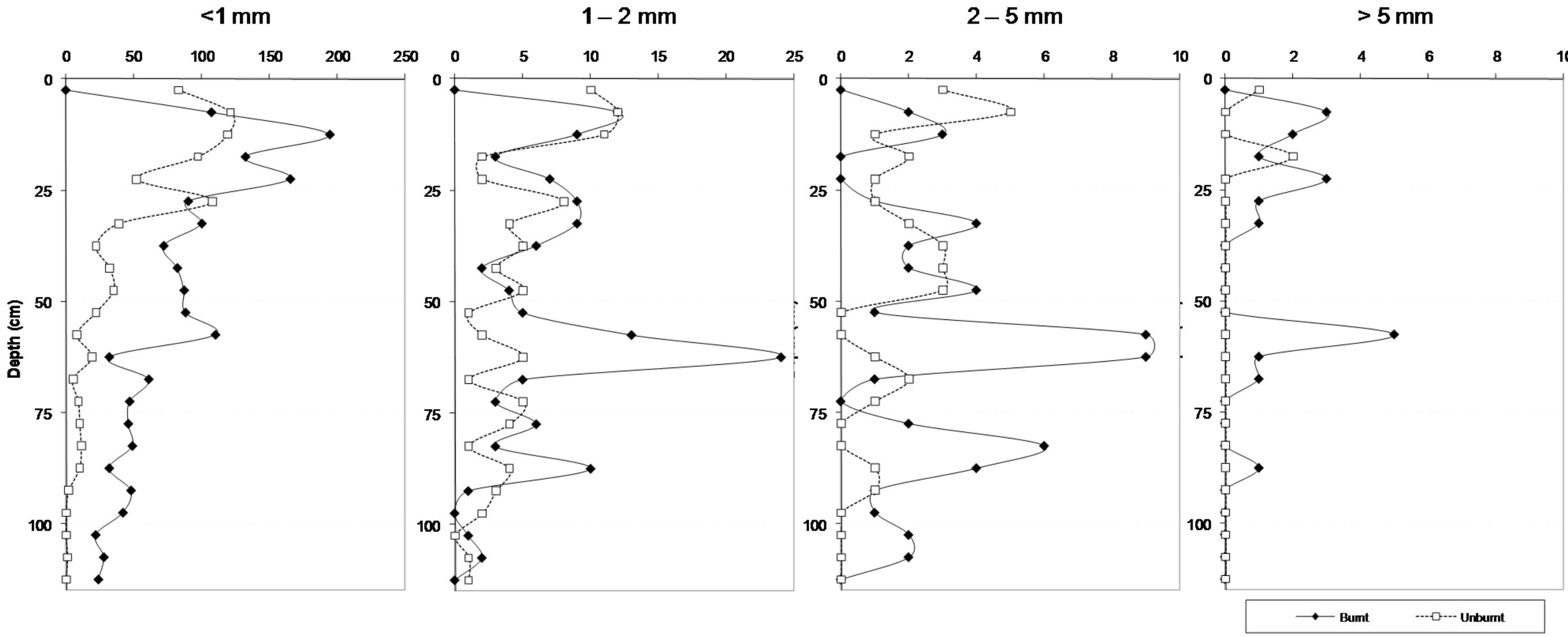

Figure 18: Sauvignon Blanc root numbers with depth of different root size classes. The Kurosol-Burnt profile had substantially more fine roots (< 1 mm) throughout the entire profile.

Table 12: Total root numbers for the respective soil profiles. Numbers in brackets indicate the percentage of the total root observations for each profile.

	Root numbers				
	< 1mm	**1-2 mm**	**2-5 mm**	**> 5mm**	**Total**
Kurosol-Burnt	1685 (88.8)	134 (7.2)	56 (3.0)	19 (1.0)	1867 (100)
Kurosol-Scalped	805 (86.6)	92 (9.9)	30 (3.2)	3 (0.3)	930 (100)

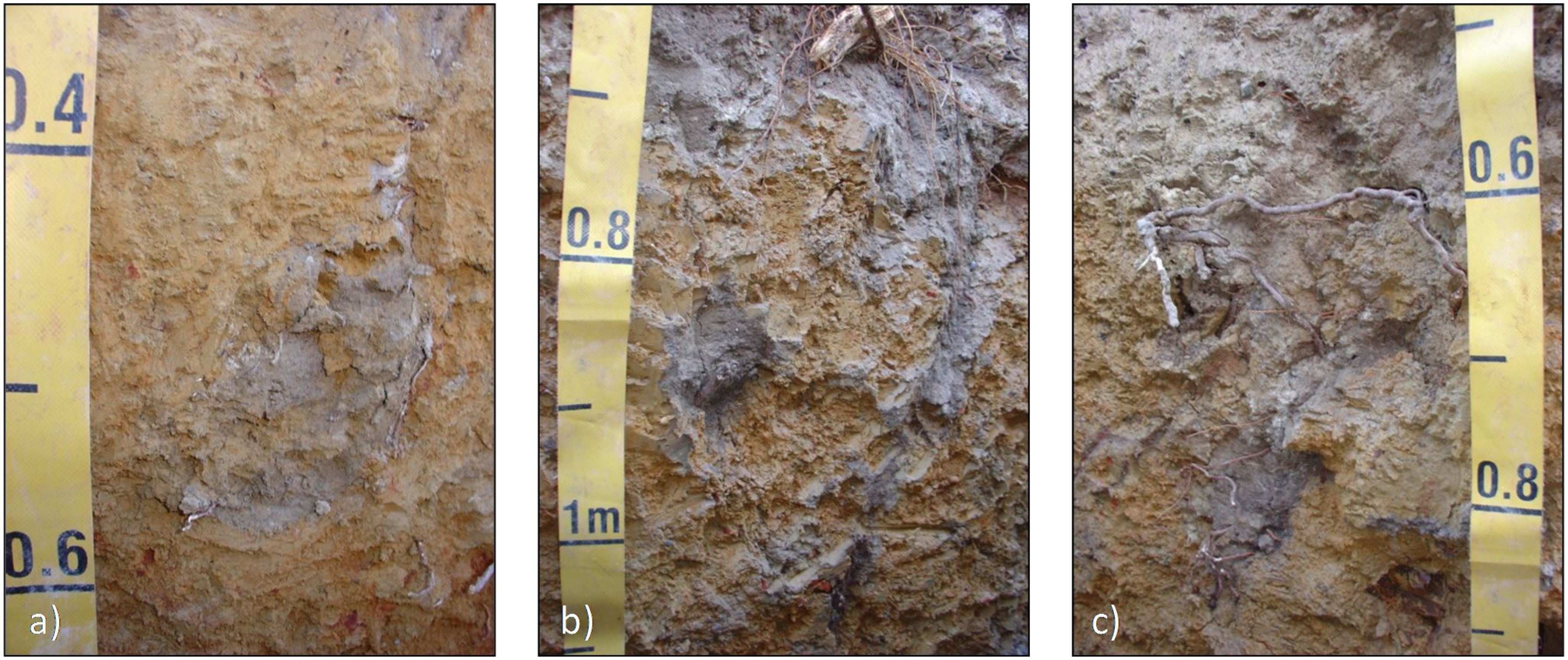

Figure 19: Examples of cracks in-filled with sandy topsoil material showing concentrations of root growth within the sandy (grey) regions. Profiles are Kurosol-Burnt (a) and Kurosol-Scalped (b, c)

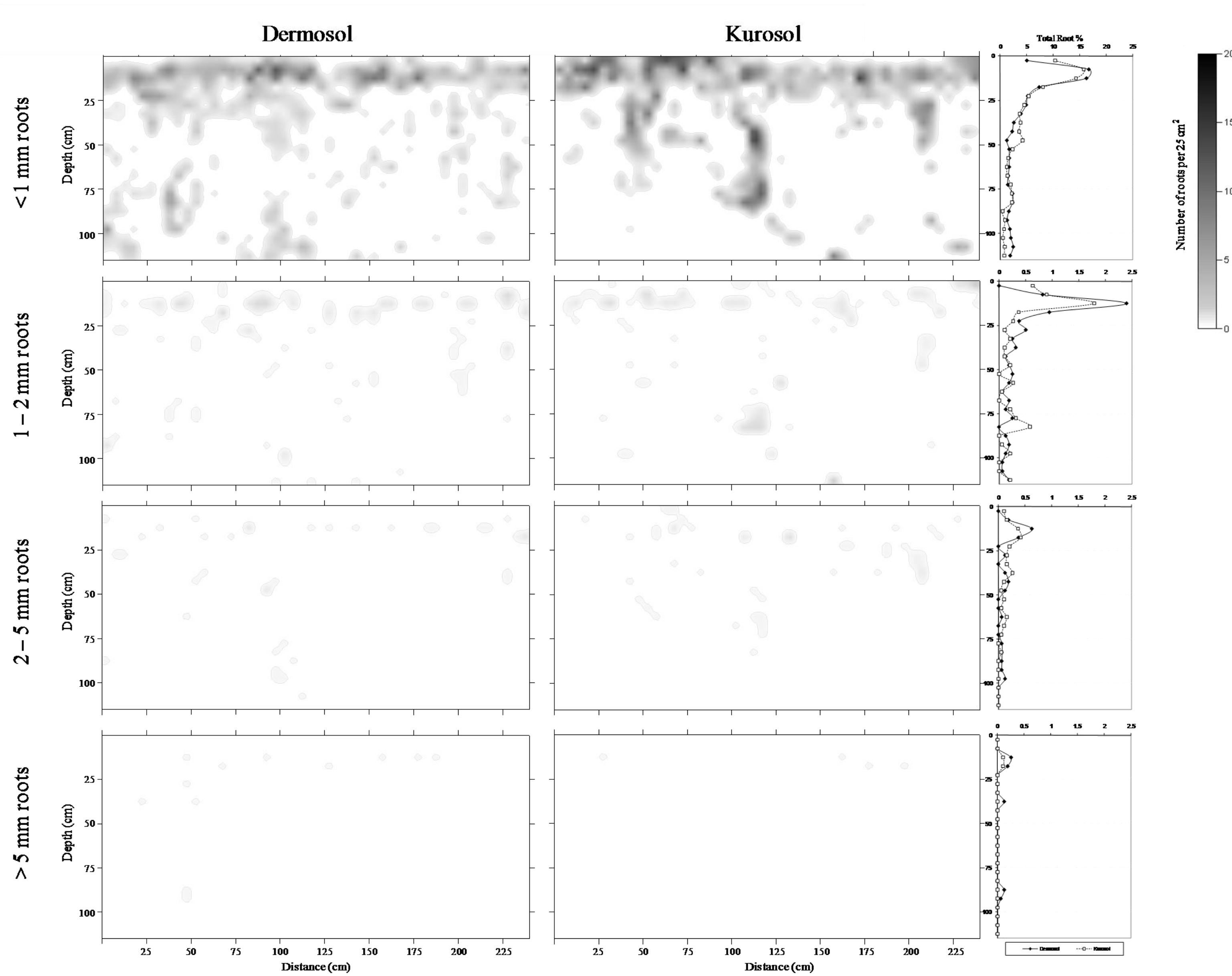

Figure 20: Pinot Noir root distribution for the Dermosol (left) and Kurosol (right) profiles showing the distribution of the following diameter classes: a) < 1mm; b) 1 – 2 mm; c) 2 – 5 mm; d) > 5 mm. Darker shading indicates higher root density. The right-hand graph shows the percentage of total roots for each size class with depth. Note: the scale for < 1 mm root class is ten times greater than the other classes demonstrating the abundance of this root size class.

Root numbers with depth for different root size classes at the Dermosol and Kurosol-Sodic profiles

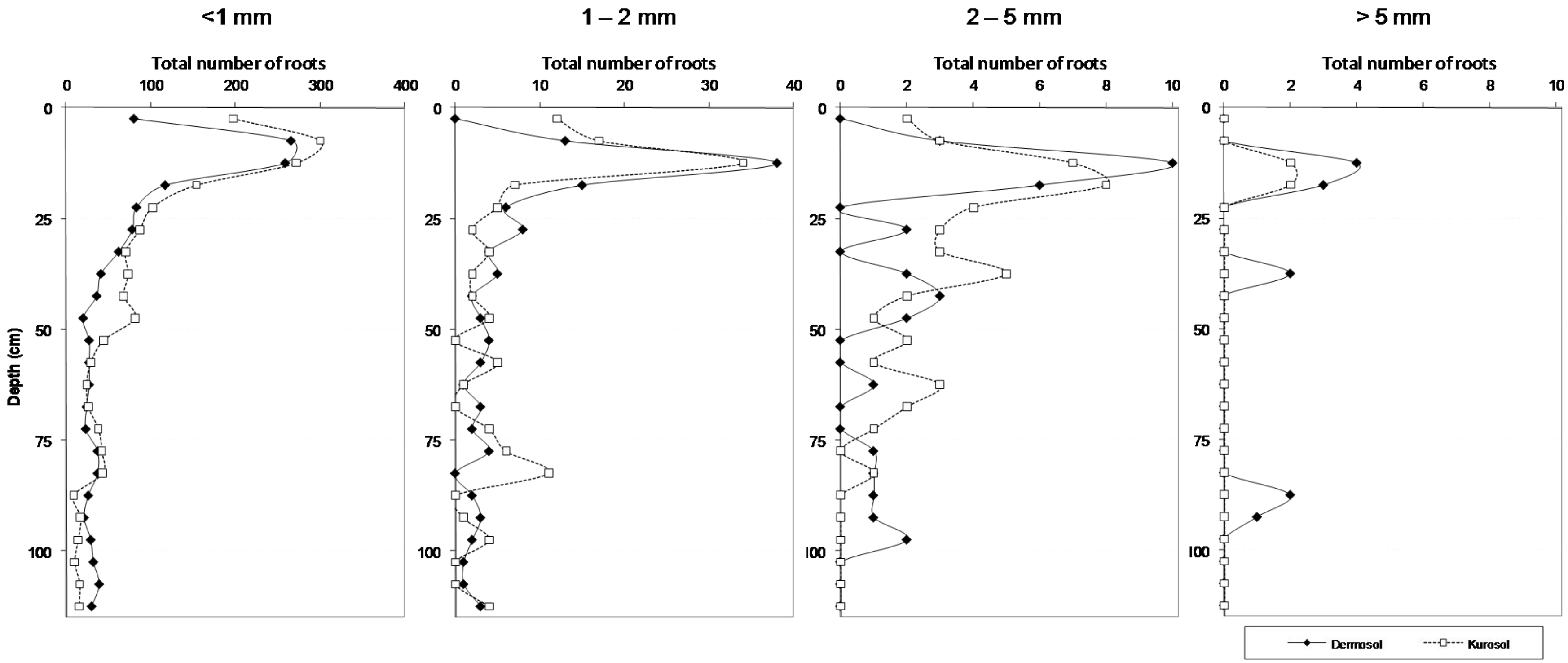

Figure 21: Pinot Noir root numbers with depth for different root size classes. Root numbers were very similar between the two profiles, with the Kurosol-Sodic having slightly higher numbers than the Dermosol.

Table 13: Total root numbers for the respective soil profiles. Numbers in brackets indicate the percentage of the total root observations for each profile.

	Root numbers				
	< 1mm	**1-2 mm**	**2-5 mm**	**> 5mm**	**Total**
Dermosol	1421	123	35	12	1591
	(89.3)	(7.7)	(2.2)	(0.8)	(100)
Kurosol	1731	125	48	4	1908
	(90.7)	(6.6)	(2.5)	(0.2)	(100)

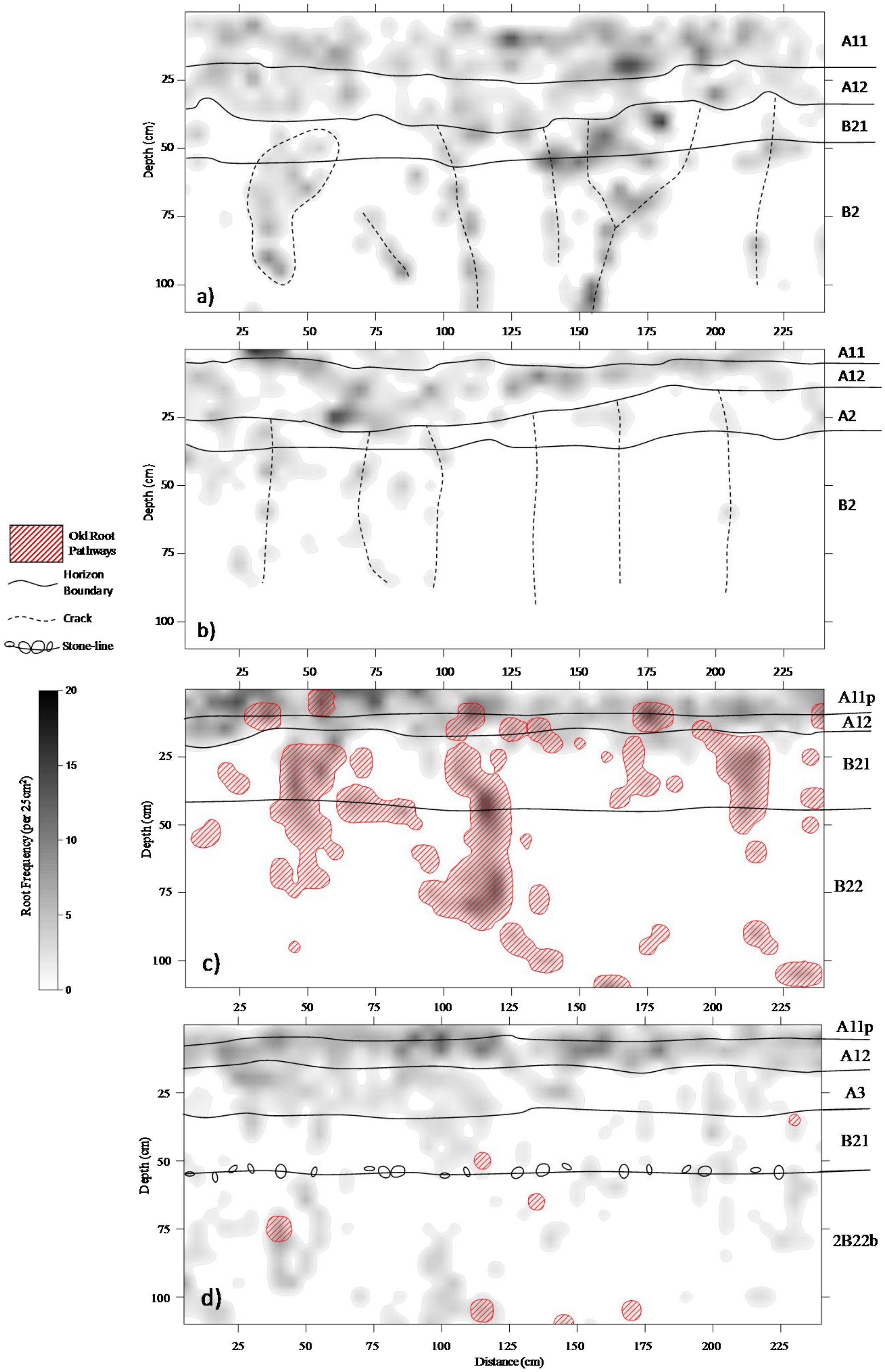

Figure 22: Fine root distribution (< 1 mm) with main horizon features overlain. Profiles are: a) Kurosol-Burnt; b) Kurosol-Scalped; c) Kurosol-Sodic; and d) Dermosol. Note that almost all subsoil root observations relate to major cracks in (a) and (b), and to within old roots (c). This contrasts with the root growth in (d). The circular crack feature on the left-hand side of (a) signifies that the observed crack was parallel to the profile face (see Figure 19a for an example).

Multivariate analysis of penetration resistance and root distribution

Two-factor loading plots describing analysis of root distribution and penetration resistance are shown in Figure 23. These plots account for approximately half of the variation observed from the different profiles (50.0 %, 54.0 %, 49.3 % and 48.7 % for Kurosol-Burnt, Kurosol-Scalped, Kurosol-Sodic and Dermosol respectively). Table 14 shows that the majority of the relationships were significant, however the correlations were generally weak. The loading plots demonstrate penetration resistance (MPa) and depth were closely related as they were plotted closely clustered together. At the Sauvignon Blanc site, these two factors have the strongest correlations of all the analysed factors with positive correlations of 0.75 and 0.80 for Kurosol-Burnt and Kurosol-Scalped respectively (Table 14). While a similar relationship is demonstrated on the loading plots for the Kurosol-Sodic and the Dermosol profiles, the correlations are lower at 0.29 and 0.44 respectively. Strong correlations were also generally found between the fine roots (< 1 mm) and either depth or MPa. On the loading plots, this root class was directly opposed to both MPa and depth, signifying a negative relationship. This was supported with negative correlations between these factors for all profiles indicating that the numbers of fine roots decline as MPa or depth increase.

Within the Sauvignon Blanc site root occurrence was strongly correlated between adjacent root size classes. For example, the < 1 mm roots had the strongest correlation with the 1 - 2 mm roots and the lowest correlation with the > 5 mm roots, whereas the 1 - 2 mm roots had stronger correlations between both the < 1mm roots and the 2 - 5 mm roots than with > 5 mm roots. Higher correlations were generally observed between root sizes at the Kurosol-Scalped profile. The strongest of these occurred between the distribution of < 1 mm and 1 - 2 mm roots. Here the correlation coefficient was 0.44 which was similar to the correlation between these roots and depth (albeit a positive rather than negative relationship). In comparison, the corresponding correlation coefficient was only 0.23 at the Kurosol-Burnt profile. The Kurosol-Sodic profile showed similar relationships between the 1 - 2 mm and 2 - 5 mm roots as well as the 2 - 5 mm and > 5 mm roots (correlation coefficients of 0.26 and 0.28 respectively). In contrast, the Dermosol profile had substantially lower correlation coefficient (< 0.05) between all root classes except for between the 2 - 5 mm and > 5 mm roots that had a correlation coefficient of 0.25.

Table 14: Pairwise correlations between root size classes, soil penetration resistance and soil position.

Indices		Correlation coefficient			
		Kurosol-Burnt	Kurosol-Scalped	Kurosol	Dermosol
MPa	Distance	0.0555	0.2237	-0.0519	-0.1449
MPa	Depth	0.7546	0.7986	0.2873	0.4361
< 1 mm	Distance	0.0327	-0.1931	-0.0812	-0.1974
< 1 mm	Depth	-0.3238	-0.4494	-0.5136	-0.4592
< 1 mm	MPa	-0.3977	-0.5968	-0.5415	-0.5510
1-2 mm	Distance	-0.0554	-0.1454	-0.0770	-0.0810
1-2 mm	Depth	-0.0703	-0.1871	-0.1096	-0.1953
1-2 mm	MPa	-0.1740	-0.2870	-0.0143^{n}	-0.0458*
1-2 mm	< 1 mm	0.2333	0.4414	0.0625	0.0912
2-5 mm	Distance	-0.0578	-0.1391	-0.0524	0.1992
2-5 mm	Depth	0.0193^{n}	-0.1440	0.0072^{n}	0.0052^{n}
2-5 mm	MPa	-0.0723	-0.1948	-0.0221^{n}	-0.0395*
2-5 mm	< 1 mm	0.2025	0.2693	-0.0601	-0.0358*
2-5 mm	1-2 mm	0.2914	0.2053	0.2625	-0.0175^{n}
> 5 mm	Distance	-0.1213	-0.0605	-0.1392	0.0998
> 5 mm	Depth	-0.0817	-0.1011	-0.0696	0.0464*
> 5 mm	MPa	-0.1182	-0.1210	-0.0480	0.0139^{n}
> 5 mm	< 1 mm	0.0619	0.0614	0.0168^{n}	-0.0302*
> 5 mm	1-2 mm	0.0941	0.0765	0.1830	0.0250^{n}
> 5 mm	2-5 mm	0.1752	0.2043	0.2830	0.2521

All values are significant (P<0.001) except were indicated with ‘n’ or ‘*’ which refer to no significance and P<0.05 respectively.

Depth = vertical depth from soil surface

Distance = horizontal distance from vine trunk

MPa = soil penetration resistance

< 1 mm, 1-2 mm, 2-5 mm & > 5 mm = respective root size classes

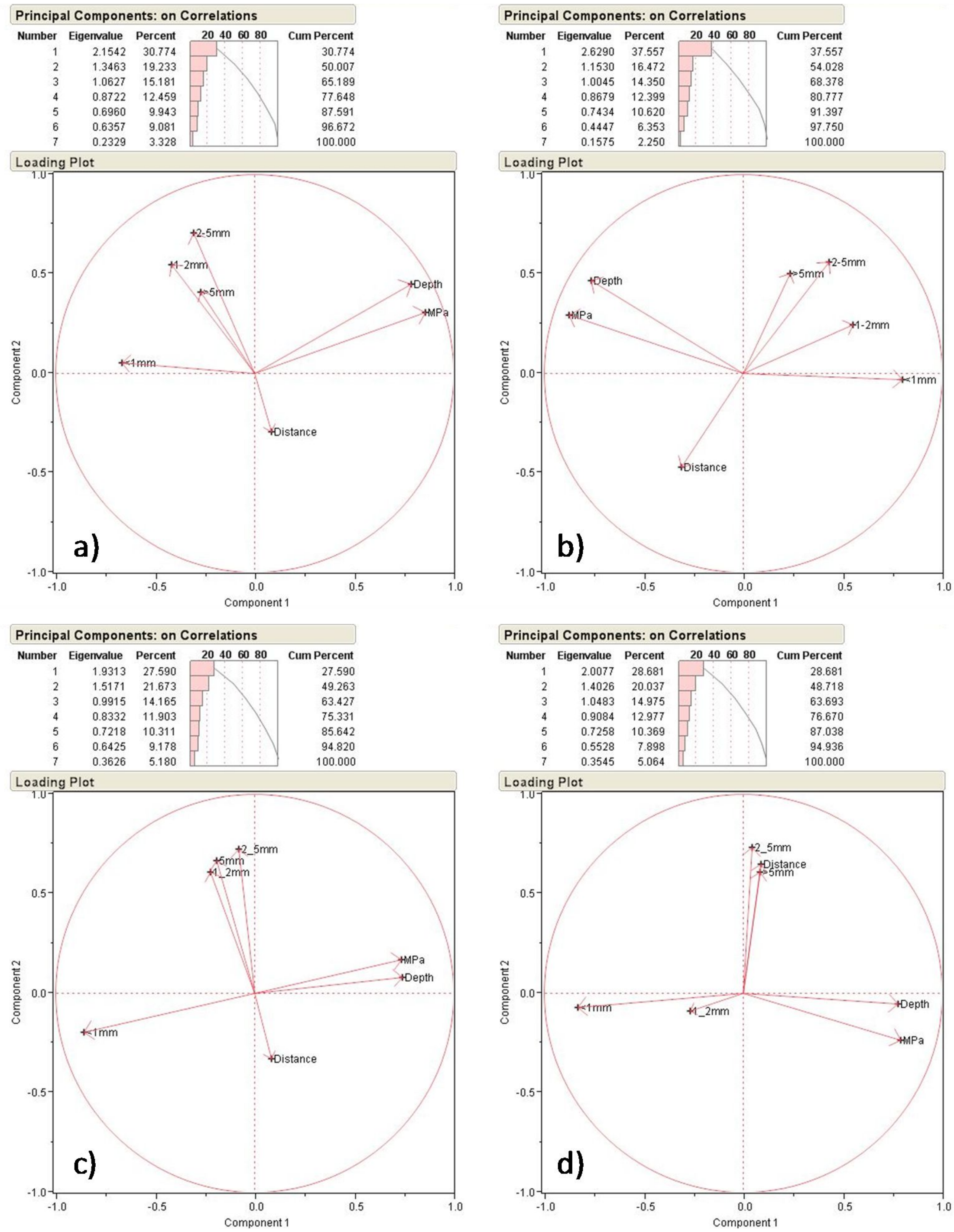

Figure 23: Two-factor loading plots of penetration resistance, root size class and soil position, Soil profiles are a) Kurosol-Burnt; b) Kurosol-Scalped; c) Kurosol-Sodic; and d) Dermosol. Factors that are plotted near each other are positively related whereas those directly opposed are negatively related.

Vine measurements

At the Sauvignon Blanc site almost all of vine parameters were significantly higher ($P<0.05$) at the Kurosol-Burnt plot than at the Kurosol-Scalped plot in each year (Table 15). The only exception was average shoot number which had no significant difference between the two plots in both 2007 and 2008. Pruning weight was nearly three times greater at the Kurosol-Burnt plot than at the Kurosol-Scalped plot. Most of these differences were related to corresponding differences (x 3) in shoot weight. Differences in yield were also substantial with the Kurosol-Burnt plot yielding just over 5 t/ha more than the Kurosol-Scapled plot in 2006 and approximately 7 t/ha in both 2007 and 2008. The greater yield at the Kurosol-Burnt site was due to a combination of greater bunch weight as well as greater bunch number.

Within the Pinot Noir site, significant differences were only observed in components of vine vigour (Table 16). Pruning weight was significantly higher ($P<0.05$) at the Dermosol and was approximately three times greater than measured at the Kurosol-Sodic. This was due to a significantly greater ($P<0.05$) cane weight of vines growing within this soil than within the Kurosol-Sodic (120 – 130 g/shoot compared to 40 – 50 g/shoot respectively). No significant differences in yield or yield components (bunch number or bunch weight) were observed between the Kurosol-Sodic or Dermosol plots. From this, the significant difference in pruning weight also resulted in the Kurosol-Sodic having significantly higher ($P<0.05$) yield to pruning weight ratio in all years. At the Kurosol-Sodic plot, this ratio increased over the study period due to increasing yield.

Selected juice and leaf analysis was undertaken by Wells (2011). No significant differences in total soluble solids (TSS) or pH were measured in juice from the Kurosol-Sodic and Dermosol profiles, however titratable acidity was significantly lower ($P < 0.05$) at the Kurosol-Sodic profile in all years (Table 17). Juice analysis was only undertaken at the Kurosol-Burnt and Kurosol-Scalped profiles in 2006 (Table 18). The juice from the Kurosol-Burnt profile had significantly higher ($P < 0.05$) total soluble solids and significantly lower ($P < 0.05$) pH and titratable acidity. Nutrient analysis of leaf lamina was also undertaken at the Kurosol-Burnt and Kurosol-Scalped profiles during veraison of 2006 (Table 19). Leaves at the Kurosol-Burnt profile had significantly higher ($P < 0.05$) nitrogen, manganese, iron and sulphur as well as significantly lower phosphorous than leaves from the Kurosol-Scalped profile.

Table 15: Vine measurement data of the Kurosol-Burnt and Kurosol-Scalped plots (Sauvignon Blanc). Different letter indicate parameter values are significantly different between plots in that year.

Parameter	Year	Kurosol-Burnt	Kurosol-Scalped
Av. Yield:Pruning weight ratio	2006	1.42 a	1.00 b
	2007	1.46 a	1.09 b
	2008	1.46 a	1.06 b
Av. Yield (kg/vine)	2006	2.50 a	0.76 b
	2007	3.11 a	0.79 b
	2008	3.22 a	0.78 b
Av. Yield (t/ha)	2006	7.40 a	2.24 b
	2007	9.20 a	2.33 b
	2008	9.55 a	2.32 b
Av. Bunch Number (bunches/vine)	2006	23.33 a	18.89 b
	2007	27.67 a	20.06 b
	2008	30.83 a	20.56 b
Av. Bunch weight (g)	2006	107.11 a	39.86 b
	2007	113.54 a	40.58 b
	2008	107.05 a	41.93 b
Av. Pruning weight (kg/vine)	2006	1.78 a	0.76 b
	2007	2.19 a	0.74 b
	2008	2.30 a	0.75 b
Av. Shoot number (shoots/vine)	2006	16.63 a	21.50 b
	2007	22.51 a	21.25 a
	2008	22.15 a	21.14 a
Av. Cane weight (g)	2006	108.69 a	36.03 b
	2007	99.94 a	35.51 b
	2008	104.24 a	37.14 b

Table 16: Vine measurement data of the Kurosol and Dermosol plots (Pinot Noir). Different letters indicate parameter values are significantly different between plots in that year.

Parameter	Year	Kurosol	Dermosol
Av. Yield:Pruning	2006	3.93 a	1.59 b
weight ratio	2007	5.00 a	1.40 b
	2008	7.07 a	1.85 b
Av. Yield	2006	3.49 a	4.05 a
(kg/vine)	2007	3.75 a	3.55 a
	2008	5.80 a	4.73 a
Av. Yield	2006	9.3 a	10.8 a
(t/ha)	2007	10.0 a	9.5 a
	2008	15.5 a	12.6 a
Av. Bunch number	2006	34.4 a	33.4 a
(bunches/vine)	2007	28.8 a	28.7 a
	2008	37.2 a	33.6 a
Av bunch weight (g)	2006	103.3 a	119.6 a
	2007	131.2 a	125.3 a
	2008	157.2 a	140.3 a
Av. Pruning weight	2006	0.90 a	2.54 b
(kg/vine)	2007	0.76 a	2.54 b
	2008	0.82 a	2.56 b
Av. Shoot number	2006	17.2 a	20.7 a
(shoots/vine)	2007	19.1 a	19.9 a
	2008	-	-
Av. Cane weightt (g)	2006	52.3 a	122.7 b
	2007	39.8 a	127.6 b
	2008	-	-

Table 17: Juice chemistry from Kurosol-Sodic and Dermosol vines (Pinot Noir). Different letters indicate parameter values are significantly different between plots in that year.

Parameter	Year	Kurosol-Sodic	Dermosol
Total soluble solids (TSS)	2006	24.5 a	25.1 a
(ºBrix)	2007	26.6 a	25.1 a
	2008	23.3 a	23.9 a
pH	2006	3.4 a	3.5 b
	2007	3.6 a	3.6 a
	2008	3.4 a	3.5 a
Titratable acidity (TA)	2006	6.6 a	7.6 b
(g/L)	2007	5.4 a	6.9 b
	2008	6.2 a	7.5 b

Table 18: Juice chemistry from Kurosol-Burnt and Kurosol-Scalped vines (Sauvignon Blanc). Different letters indicate parameter values are significantly different between plots in that year. Measurements were taken in 2006 only.

Parameter	Kurosol-Burnt	Kurosol-Scalped
Total soluble solids (TSS) (ºBrix)	22.1 a	20.9 b
pH	3.00 a	3.07 b
Titratable acidity (TA) (g/L)	8.8 a	10.0 b

Table 19: Veraison leaf lamina nutrient analysis from Kurosol-Burnt and Kurosol-Scalped vines (Sauvignon Blanc). Different letters indicate parameter values are significantly different between plots in that year. Measurements were taken in 2006 only.

Parameter	Kurosol-Burnt	Kurosol-Scalped
Total N (%)	2.4 a	1.7 b
Phosphorus (%)	0.18 a	0.25 b
Potassium (%)	1.5 a	1.5 a
Sulphur (%)	0.31 a	0.26 b
Sodium (%)	0.03 a	0.04 a
Calcium (%)	1.9 a	2.0 a
Magnesium (%)	0.39 a	0.48 a
Copper (mg/kg)	239 a	266 a
Zinc (mg/kg)	34 a	34 a
Manganese (mg/kg)	294 a	148 b
Iron (mg/kg)	100 a	73 b
Boron (mg/kg)	52 a	51 a

Discussion

Influence of parent material on soil properties

The Dermosol was the only profile examined that had soil formed in part from dolerite colluvium. This was evident in the top 55 cm of this profile with these horizons having differing XRF analysis than corresponding horizons at the Kurosol-Sodic profile. The higher Al_2O_3 and Fe_2O_3 and lower SiO_2 levels throughout these horizons at the Dermosol profile are consistent with other soils formed from dolerite and/or dolerite colluvium (Osok and Doyle, 2004; Nicolls, 1958; Tiller, 1962; Leaman, 2000). The XRF analysis of the deeper soil horizons (> 55 cm depth) were similar between the two profiles suggesting they were both formed from similar materials (Tertiary sediments). The presence of a stone-line separating these materials indicated the original upper horizons of this soil had been eroded prior to the deposition of the dolerite colluvium (Bulter, 1959). The colluvium resulted in the Dermosol having a higher clay content and a gradational texture profile, compared to a texture-contrast (or duplex) profiles in which sandy loam textures overlay clayey subsoils. All three Kurosol profiles had strongly acid subsoils (pHw < 5.5). However, the Demosol profile had pHw values greater than 5.5 within all subsoil horizons and pHw values were approximately one unit higher throughout most of the subsoil horizons (including the Tertiary Sediments). This higher subsoil pH and lack of texture-contrast horizons resulted in this profile being classified as a Dermosol, rather than a Kurosol (Isbell, 1996). The Kurosols also had a sandy A2 horizon that was not present within the Dermosol. The low pH of the Kurosol subsoils resulted in the solubilisation of aluminium, increasing the amount of exchangeable Al^{3+} measured. All of the Kurosol profiles had measurable levels of exchangeable Al^{3+} within their subsoils. In comparison no exchangeable Al^{3+} was detected at the Dermosol profile due to the higher pH values of this profile despite the high total Al_2O_3 in the soil materials. This demonstrates the importance of the more basic dolerite parent material in producing high soil pH values that minimise any potential exchangeable Al^{3+} toxicity.

Differences in soil parent materials seem to have led to the contrasting physical properties between the soil orders. The Kurosol profiles had weak to moderately developed coarse columnar primary subsoil structure. Secondary structure was also weakly developed and was generally tightly bound fine angular blocky structure. The penetration resistance of these horizons showed a positive correlation with depth and was > 2 MPa within the bulk subsoil with only discrete regions in and around sandy cracks or decaying roots had values < 1.5 MPa. The exception to this was the Kurosol-Sodic profile, where penetration resistance values were lower than the other two profiles due to the watertable increasing the moisture content throughout the subsoil.

In contrast, the Dermosol profile had strongly developed fine polyhedral peds tending towards granular structure in the surface horizons. This facilitated lower penetration resistance values than within the Kurosol profiles with almost the entire Dermosol profile having MPa values < 1.5 MPa. This friable structure was similar to other brown soils on dolerite described by both Nicolls (1958) and Laffan and McIntosh (2005) and is produced by oxidation of iron and aluminium supplied from the dolerite parent material (Nicolls, 1958; Tiller, 1962). These oxides were also responsible for the strong brown colour observed at this profile and demonstrate that this profile is readily permeable to both air and water. At the Pinot Noir site this enhanced drainage status resulted in the watertable occurring deeper within this profile than within the corresponding Kurosol-Sodic profile despite its lower landscape position. The EC of the water was also lower at the Dermosol (2 dS/m compared to 5 dS/m at the Kurosol-Sodic profile) which also corresponds to the difference in soil EC observed between these soils.

Weathering dolerite, a mafic parent material, is also a source of calcium, magnesium, sodium and potassium (Tiller, 1962). This is reflected in the Dermosol topsoil having high levels of exchangeable Mg^{2+}, exchangeable Ca^{2+} and exchangeable K^{+}. The Kurosols only achieved similar values of these cations after substantial modification such as windrowing and burning of additional organic material, as demonstrated by the Kurosol-Burnt topsoil.

The three Kurosol profiles had many similar soil chemical features demonstrating the relative uniformity of the Tertiary sediments from which these soils were formed. Along with having strongly acid subsoils, the Kurosol subsoils also became magnesic with depth (Ca:Mg ratio < 0.1) indicating the disproportionately high amount of exchangeable magnesium in the subsoils of these profiles. In contrast, the Dermosol subsoil had approximately half the exchangeable Mg^{2+} of the Kurosols and resulted in Ca:Mg ratios between 0.4 – 0.5. It is expected that the higher concentration of magnesium within the Kurosols is associated with the higher electrical conductivity values of the Kurosol-Sodic profile compared to the Dermosol.

The influence of the dolerite colluvium seems to have extended deeper into the soil below the stone-line (55 cm), as the underlying Tertiary sediments at this site also had lower exchangeable Mg^{2+} and higher pH and no exchangeable Al^{3+} than similar soil materials within the Kurosol profiles. This probably relates to the higher base status of the dolerite colluvium which has increased the pH of the whole profile.

Influence of soil properties on root distribution

Root abundance decreased with depth within all profiles, with the highest root frequency occurring within the upper 25 cm of each profile. This was similar to the vertical distribution of organic carbon, exchangeable Ca^{2+}, exchangeable K^{+} and pH which all decreased with depth. Electrical conductivity (EC), exchangeable Na^{+}, exchangeable Al^{3+} and penetration resistance all increased with depth and are thus inverse of the observed root growth. Therefore, the topsoil environment of all profiles was considered to be the most favourable for root growth and thus it was unsurprising that root growth predominantly occurred within these layers. While highest fertility generally occurred near the soil surface (0 – 10 cm), the highest root frequency generally occurred lower in the soil profile at depths between 10 – 25 cm. Lack of root growth in the surface layer was attributed to increased soil temperature, increased evaporation and decreased moisture availability. Across all soil profiles, the percentage distribution between the root sizes remained consistent. Approximately 85 – 95 % of all roots were < 1 mm in size with the remaining size classes accounting for 7 – 10 %, 2-3 % and < 1% (1 – 2 mm, 2 – 5 mm and > 5 mm respectively). This indicated that the subsoil properties influenced the number of roots, but not the size distribution of the roots. In comparison to the other sites the Kurosol-Scalped profile had lower root number (approximately half of all other profiles) and low soil fertility including substantially less organic carbon and reduced exchangeable cations (Ca^{2+}, Mg^{2+} & K^{+}) compared to the other profiles, as much of the original topsoil was removed prior to establishment.

Similar root numbers were observed within the topsoil of the other the Kurosol-Burnt, Kurosol-Sodic and Dermosol profiles despite differences in soil chemistry and grapevine variety. Of these profiles, the Kurosol-Sodic had lowest values of exchangeable K^{+} and exchangeable Mg^{2+} and highest values of exchangeable Na^{+} and EC compared to the other two profiles. This suggests that the values were either adequate for root growth (in the case of K^{+} and Mg^{2+}) or non-inhibiting (in the case of Na^{+} and EC). The value of exchangeable Na^{+} is particularly important as it suggests that sodium concentration up to 2.1 cmol(+)/kg is non-limiting to vine root growth. Likewise, exchangeable Mg^{2+} values greater than 3.5 cmol(+)/kg are likely to be non-limiting to root growth in grapevines. However, care is needed with interpretation of this value as supplementation of exchangeable Mg^{2+} could be occurring from the higher values lower in the profile.

The substantial difference between root growth and topsoil chemical properties of the Kurosol-Burnt and Kurosol-Scalped profiles demonstrates the beneficial effect of windrowing and burning on topsoil fertility and root growth. The Kurosol-Burnt profile had over twice the values of organic carbon and exchangeable cations (particularly Mg^{2+} and K^{+}) within the topsoil than the corresponding Kurosol-Scalped soil. The horizon was also twice as thick within the Kurosol-Burnt profile. These differences are likely to be from the stockpiling and subsequent burning of the previous vegetation. Fire has been well documented to increase the availability of nutrients in surface horizons (Humphreys and Lambert, 1965; Chambers and Attiwill, 1994; Ludwig *et al*, 1998) and is the most likely cause of the observed differences in nutrients. Fire is also associated with an increase of topsoil pH (Ellis and Graley, 1983; Guinto *et al*, 2001) however Binkley *et al* (1992) demonstrated this may be short-lived and the final pH will actually be lower than original values. The observation of lower topsoil pH of the Kurosol-Burnt profile compared to the Kurosol-Scalped profile supports this finding, however the difference was not considered to have influenced root growth. Instead, the root growth within the Kurosol-Burnt profile reflects the increased availability of nutrients and thicker topsoil which has led to substantially greater root numbers than the Kurosol-Scalped profile.

Root growth was constrained within the subsoils of all Kurosol profiles especially compared to the Dermosol profile. This was particularly evident with the distribution of fine roots (< 1 mm) that clearly showed restricted growth to either sand-filled cracks (Kurosol-Burnt and Kurosol-Scalped profiles) or within prior old roots (Kurosol-Sodic profile, see Figure 22). In contrast, the friable structure of the Dermosol allowed more diverse root distribution and only limited associations with prior old roots were observed. The Kurosols also had stronger correlation coefficients between root size classes indicating that these constraints were not only limited to the fine roots and that the different root sizes were clustered together in the same location compared to root growth within the Dermosol.

The strongly acid subsoils ($pH_w < 5.5$) of the Kurosols are considered an impediment to root growth (Himelrick, 1991; Baligar, 1998; Conradie, 1988; Delas, 1994) and a potential cause of the restricted root distributions observed. Low pH inhibits root growth through aluminium toxicity (Foy, 1992; Baligar, 1998) with the critical value of exchangeable Al^{3+} for vine growth recommended to be 50 mg/kg (Delas, 1984). This limit was exceeded in the subsoil of the Kurosol-Burnt profile at depths greater than 40 cm and values exceeded 150 mg/kg below 60 cm. In contrast, the other Kurosol profiles both had lower levels of exchangeable Al^{3+} with only depths below 115 cm at the Kurosol-Scalped profile exceeding 50 mg Al/kg. No exchangeable Al^{3+} was detected at the Dermosol due to the higher base cation content and high pH values of this profile. Consequently a greater impediment to root growth would be expected at the Kurosol-Burnt profile and no impediment would be expected at the Dermosol profile. Despite the subsoil pH, substantial root growth was observed within the Kurosol-Burnt profile with roots observed at depths below 120 cm. This suggests that the measured exchangeable

Al^{3+} was either not an impediment to root growth or that the conditions within the sandy cracks (and prior old roots) were more favourable to root growth than indicated by bulk soil chemistry. Toxic aluminium conditions characteristically cause 'crinkled' vine root systems or 'stubby root syndrone' (Sumner, 2005). These were not observed, indicating that aluminium levels were most likely non-toxic in these regions. Bates (2002) demonstrates that vine roots can alter the pH of the rhizosphere depending on the pH of the bulk soil. At low pH (pH 4.0, 1:1 soil:water) the rhizosphere was 0.4 units higher than the bulk soil. It is expected that any alteration of pH would be easier within sandy soils compared to clayey soils, due to the lower ECEC of the sands. Therefore roots growing through the sandy cracks would potentially have greater influence over the rhizosphere pH and consequently experience less exchangeable Al^{3+} than that measured from within the bulk soil. As the aluminium is primarily sourced from clays (alumina-silicates) this also fits with greater root growth within the sandy cracks. While exchangeable Al^{3+} of the sandy cracks was not directly measured, it is likely to have had much lower exchangeable Al^{3+} as this material was washed down the cracks from the overlying A12/A2 horizons which had lower exchangeable Al^{3+}.

Within the Kurosol-Sodic profile, the increased levels of organic matter within the prior old roots may bind with Al^{3+} through complexes with various organic acids (Hue *et al*, 1986). This would make it a more favourable environment for root growth. Van Noordwijk (1991) demonstrated that old decayed tree root channels are important for root penetration of maize growing through acid soils and contrasted the severe Al toxicity symptoms observed in roots growing without these channels i.e. directly within the acid subsoil.

In the previous studies of low pH soils, the high levels of aluminium generally inhibited root growth within the subsoil horizons and vines had a shallow root system (Himelrick, 1991; Baligar, 1998; Conradie, 1988; Delas, 1994). This was not observed at both the Kurosol-Burnt and Kurosol-Sodic profiles where the sandy cracks and prior old roots have enabled root growth to occur deep into the subsoil (> 1 m). Results demonstrate that while roots were avoiding the Al^{3+} rich soil, it was the horizontal rather than the vertical distribution of the roots that was restricted within these profiles. Bennet and Breen (1989) have shown that the root cap perceives aluminium similar to mechanical impedance. Therefore roots grow through the sandy cracks and prior old roots that are chemically distinct to those regions within the Kurosol profiles. The study data indicate that once vine roots are within a sand-filled crack or an old root, they are unlikely to re-enter the high exchangeable Al^{3+} subsoil clays.

Mechanical impedance of vine root growth occurs when the penetration resistance of the soil exceeds 2 MPa, measured at field capacity (Van Huyssteen, 1983; Myburgh *et al*, 1996). Both the Kurosol-Burnt and Kurosol-Scalped profiles exceed this value throughout most of their subsoils and only the sandy cracks have lower penetration resistance values. Consequently, there are both chemical and physical constraints to root growth within the soil matix which limits root elongation to the sandy cracks and prior old roots.

While the Kurosol-Sodic profile had penetration resistance less than 2 MPa, the moisture content of this profile was higher than field capacity due to the high water table. It was expected that the penetration resistance would exceed 2 MPa within the subsoil when this profile is drier. Nonetheless, at the time of measurement the prior old root channels still had lower penetration resistance than the surrounding soil. As a result, root growth within all the soil profiles was located where the measured penetration resistance was lowest. This is consistent with McKenry (1984) who also observed prolific grapevine root growth within biopores created by dead and decomposing roots.

The high penetration resistance in the subsoil of the Kurosol profiles was attributed to the clayey textures and poor and coarse structure typically associated with high exchangeable Mg^{2+} and exchangeable Na^{+}. Magnesium and sodium are known to cause structural instability when soils are wet and create poor physical properties at low moisture contents (Rengasamy and Olsson, 1991) Both the sandy cracks and prior old root channels that occurred within the Kurosol subsoils help stabilise these regions of the soil profile. They could also be responsible for preferential water movement through the profile, especially where they connect to the topsoil horizons. Hardie (2011) has demonstrated preferential water flow systems are prevalent within texture-profiles in south-eastern Tasmania and it is highly likely that similar water flow pathways occur in the currently studied profiles. This would mean these areas are first to recharge following rainfall or irrigation and will be the first to drain after saturated conditions. This was demonstrated at the Kurosol-Sodic profile where gleyed and waterlogged soil was observed beneath the larger old root channels (Figure 14a). Old root channels have also been shown to preferentially flush salts away from roots (Bramley *et al*, 2003). Consequently vine roots growing within the old root channels at the Kurosol-Sodic profile would be less affected by the saline conditions from the seasonal water table than roots growing through the bulk soil. Therefore, within all of the observed Kurosol profiles the vine roots are avoiding much of the adverse subsoil conditions (high penetration resistance, low soil pH and/or shallow saline watertable) by growing through either the sandy cracks or prior old roots. Such adverse conditions have severely constrained the root distribution to isolated sections of the soil profile. These adverse conditions were not observed within the Demosol profile and subsequently the root distribution was more widespread (see Figure 22 for comparisons of fine root distribution).

Even though similar subsoil constraints were observed at both the Kurosol-Burnt and Kurosol-Scalped profiles, the observed root distribution was substantially greater at all depths within the Kurosol-Burnt profile (Figure 17 and Figure 18). This was attributed to the increased topsoil depth and nutrient content of the Kurosol-Burnt profile. Along with increased nutrients, the over-thickened topsoil will also have a greater capacity to store moisture. This was reflected in the estimations of PAW with the Kurosol-Scapled profile only having a PAW of 66.7 mm within the effective rooting depth (90% of root observations) compared to 95.8 mm within the Kurosol-Burnt profile. It is hypothesised that these properties have allowed the vine roots greater resilience to explore and survive through more of the unfavourable zones of the soil profile compared to the Kurosol-Scalped profile even though subsoil conditions were similarly hostile. This hypothesis was supported with the clear variation between the two vines in the Kurosol-Scalped profile where differences in topsoil thickness were also observed laterally across the

Kurosol-Scalped profile (Figure 22b). Limited subsoil root growth occurred in this part of the profile, where the topsoil was less than 20 cm thick (excluding A2 horizon).

While differences in root distribution and root restrictions were observed across the soil profiles, total root numbers were relatively similar between the Kurosol-Burnt, Kurosol-Sodic and Dermosol profiles (total root counts of 1862, 1908 and 1591 respectively). This shows that the subsoil restriction of the Kurosol-Burnt and Kurosol-Sodic profiles did not reduce root numbers compared the unconstrained conditions of the Dermosol. Furthermore, the constriction seems to have increased root numbers for these profiles with 200 – 300 more roots (mostly < 1 mm) compared to the same depth within the Dermosol profile. This is consistent with Zhang and Bravdo (2001) who found root restriction resulted in more fine roots (< 0.5 mm) and less medium roots (0.5 – 3 mm) of pot grown grapevines (cv. Cabernet Sauvignon). As these fine roots generally have shorter lifespans in grapevines compared to coarse roots (Anderson *et al*, 2003) an increase in fine root abundance could signify increased root turnover in the Kurosol-Burnt and Kurosol-Sodic profiles compared to the Dermosol profile.

Influence of root distribution and root function on vine growth

Significant differences in vine vigour were observed in soils with high soil nutrition and increased topsoil thickness. At the Pinot Noir site this occurred through natural differences between contrasting soil types (Dermosol compared to the Kurosol-Sodic). Whereas within the Sauvignon Blanc site it was related to windrowing and burning modifications of a previously similar soil type (Kurosol-Burnt compared to Kurosol-Scalped).

The relationship between total root numbers and vine growth (pruning weight and fruit yield) was not consistent between the profiles studied. At the Sauvignon Blanc site, the greater root numbers of the Kurosol-Burnt profile related to significantly higher ($P < 0.05$) pruning weight and fruit yield compared to the Kurosol-Scalped profile. However at the Pinot Noir site, the Kurosol-Sodic had significantly lower ($P < 0.05$) pruning weight but higher total root number compared to the Dermosol profiles. At this site, no significant yield difference was observed between the two profiles in any year.

Vine vigour was moderate to high across all vines measured. According to Smart and Robinson (1991), mean cane weights of 20 to 40 grams indicate moderate vigour, while weights exceeding 60 grams indicate high vigour. Therefore even though both the Kurosol-Scalped and Kurosol-Sodic plots had considerably less growth, they both can be considered to have moderate vigour (average cane weights of 35 – 45 grams). In contrast, both the Kurosol-Burnt and Dermosol plots had average cane weights of 100 – 130 grams and are therefore considered to be highly vigorous. It was hypothesised that the higher canopy density of the Dermosol led to excessive shading of buds that reduced the number of bunches per shoot. This is consistent with Cortell (2005) who found that higher yields in Pinot Noir were obtained from moderately vigorous vines, compared to vines of both higher and lower canopy vigour. This suggests that increasing canopy vigour from low to moderate levels can lead to increases in fruit yield, but once canopy vigour reaches a critical value a decline in fruit yield will occur. Any increase in canopy vigour can lead to a greater availability of carbohydrates and vigour resulting in enhanced accessibility for fruiting (Clingeleffer and Sommer, 1995). However an excessive canopy decreases air movement and light exposure through the canopy and reduces fruitfulness and fruit set (Dry, 2000; Smart and Robinson, 1991).

The inconsistent relationship observed between root numbers and vine vigour suggests that root function is more important to above ground vine growth than just total root abundance. The comparison within the Pinot Noir site clearly demonstrates the Kurosol-Sodic profile had higher root numbers but lower vigour than the Kurosol-Burnt profile. Root function has previously been shown to be an important consideration for both nutrient and water uptake (Richards, 1983; Cass, 2004) and it is likely that uptake by the roots is different between the soils examined. Limited soil moisture holding capacity, lack of aeration for root respiration (waterlogging) or hard and compact soil can all limit root function (Richards, 1983). All of these factors were observed within the Kurosols studied.

At both the low vigour profiles (Kurosol-Scalped and Kurosol-Sodic) the estimated plant available water (PAW) within the root zone was lower than that estimated for the corresponding high vigour profiles (Kurosol-Burnt and Dermosol respectively). This indicates greater availability of soil moisture is important for vine growth. Roots within the low vigour profiles were also more constrained than corresponding high vigour profiles. Both these factors limit the vines access to water and nutrients. Nutrient flow within the soil is generally either by diffusion through the soil solution or by mass flow of the soil solution (Cass, 2004). The uptake of nutrients often depends on one or more of these mechanisms depending on their concentration in the soil solution. Tinker and Nye (2000) summarise that the uptake of sulphur, calcium, sodium and magnesium is generally satisfied by mass flow whereas potassium, phosphorous, nickel, copper, iron, manganese and zinc normally have a large diffusion component in their uptake, due to their generally low concentration in the soil solution. However, as diffusion of nutrients towards the roots is generally slower and has a smaller spatial range than mass flow (Cass, 2004) the uptake of the latter elements commonly require a degree of root interception for adequate uptake. This could explain why high root numbers were measured within the Kurosol-Burnt and Kurosol-Sodic profiles even though the root distribution was constrained to the sandy cracks and prior old roots. In well-structured soils, connective flux towards roots and subsequent access to water and nutrients is higher than in soils with poor internal structure (Cass, 2004). Therefore roots growing through the Dermosol are likely to be more efficient at nutrient and water uptake than those growing through the Kurosols. This may explain why vine vigour was high at the Dermosol despite having slightly lower root numbers than the other profiles.

The constraints to root growth within the Kurosol profiles occurred through a combination of low pH, high penetration resistance (> 2 MPa) and/or a shallow saline watertable. These factors are also thought to have influenced above ground vine growth. Numerous studies have demonstrated that low soil pH decreases vine growth (Conradie, 1983; Delas, 1984; Himelrick, 1991; Velemis *et al*, 1998; Kirchhof, 1991; Bates *et al*, 2002; Conradie *et al*, 2002). Bates *et al* (2002) also observed that while reductions to growth occurred both above and below ground, the vegetative growth was more affected than the root biomass. This corresponded to an increase in aluminium and iron within the grapevine tissue and decreased tissue concentrations of both potassium and calcium (Himelrick, 1991; Bates *et al.*, 2002). This re-enforces the importance of root function modifying vine growth. High exchangeable Al^{3+} within the soil can precipitate phosphorus making it unavailable for root uptake, and exchangeable Al^{3+} can also displace calcium and magnesium decreasing their availability (Foy, 1992). Aluminium may also inhibit the uptake of calcium by blocking the calcium channels of the root membrane (Huang *et al* 1992) through its greater affinity (560-fold) for phospholipids in membranes (Akenson *et al*, 1989).

Leaf nutrient analysis undertaken by Wells (2011) indicates that vines at the Kurosol-Burnt profile had significantly lower ($P < 0.01$) phosphorous and significantly higher manganese and iron than vine leaves at the Kurosol-Scalped plot. This reflects the difference in soil pH and aluminium measured between these soils and shows that the low pH and high exchangeable Al^{3+} of the Kurosol-Burnt profile has influenced leaf nutrition. No difference in leaf calcium or magnesium was observed between the two profiles.

While the Kurosol-Burnt and Kurosol-Sodic profiles had high root numbers, the low pH of these profiles is expected to have reduced the nutrient availability for plant use and thus limiting vine growth. The influence of this would be greater where other nutrient sources are limited or not available. Consequently, vines growing at the Kurosol-Scalped and Kurosol-Sodic profiles are more affected by the low subsoil pH than those at the Kurosol-Burnt profile, due to their thinner topsoils and lower topsoil fertility. The total nitrogen content of vine leaves at the Kurosol-Burnt and Kurosol-Scalped profiles reflect this difference in nutrition, with significantly higher nitrogen concentration measured from the Kurosol-Burnt profile.

The result of topsoil scalping at the Kurosol-Scalped profile has not only reduced vine growth through decreasing topsoil fertility. The removal of topsoil has also meant the compact subsoil was closer to the soil surface and thus the volume of soil available for root elongation (< 2 MPa) was limited. This decreases vine growth by reducing the amount of soil roots can explore to uptake nutrients and soil moisture (Van Huyssteen, 1983; Myburgh *et al*, 1996; Zhang and Bravdo, 2001). Root growth can still occur through these soils if cracks are present through the profile, however the functionality of the roots within the cracks can be reduced due to poor aeration or poor water availability (Dexter, 1988). This leads to reduced uptake efficiency of both water and nutrients (Passioura, 1988; 1991; Tardieu *et al*. 1992). It also leads to a high concentration of roots within a small volume of soil and hence localised nutrient depletion in the rhizosphere. Therefore any roots growing within sand-filled cracks at both the Kurosol-Burnt and Kurosol-Scalped profiles will have less participation in nutrient uptake than if they were growing in unrestrained soil. However, as the Kurosol-Burnt profile has adequate nutrients in the surface horizons, there is less need for the subsoil roots to take up nutrients. It seems these roots are enabling these vines with greater access to soil moisture than vines growing at the Kurosol-Scalped profile and therefore less prone to droughty soil conditions. Conradie (1988) demonstrated that vines roots are also an important source of nutrient reserves during the early part of the growing season as well as coming into harvest. Therefore the increased root system within the Kurosol-Burnt profile provides a greater buffer and robustness to these vines and leads to sustained vine growth. Whereas the reduced root system within the Kurosol-Scalped profile means these vines experience greater fluctuations in nutrient and moisture access and have longer periods of reduced or no vine growth.

Vine growth was also affected by subsoil root constrictions at the Kurosol-Sodic profile. However at this soil, the greatest restriction to the root growth occurred through waterlogged soil conditions. Saturated soil conditions reduce soil aeration and therefore limit oxygen supply which is needed for vine root metabolism and nutrient uptake (Lambers *et al*, 2002). Prolonged waterlogging can also cause ions to leak into the soil from the root epidermis and/or root death (Huang, 2005). Therefore at the Kurosol-Sodic profile vine growth is not only suppressed during a waterlogging event through poor nutrient uptake, nutrient loss and/or root death, but is also potentially suppressed through the requirement to either re-grow new roots or re-uptake lost nutrients once the waterlogged conditions have been removed. Once waterlogged conditions are removed, it is expected that root growth and subsequent nutrient uptake will be further impeded due to the drier soil having an anticipated high penetration resistance of the subsoil.

The salinity of the watertable (5 dS/m) at the Kurosol-Sodic profile would also be contributing to the reduction in vine growth. Grapevines are moderately sensitive to salinity (Mass and Hoffman, 1977). Stevens *et al* (1999) showed that irrigation with saline water (3.5 dS/m) reduced both vine growth and fruit yield. Of the yield components, reduction of berry weight was the most sensitive. Vines growing at the Kurosol-Sodic profile also had significantly lower ($P < 0.05$) bunch weight than those at the Dermosol profile (40 grams per bunch compared to 110 grams per bunch respectively) indicating that the saline watertable within the Kurosol-Sodic profile has affected fruit yield.

Across the studied soils root distribution and vine growth was highly impacted by soil properties. The soils formed from Tertiary sediments all had critical impediments to root growth. At the Kurosol-Burnt and Kurosol-Scalped profiles, severe root restriction occurred through the high penetration resistance and low pH of the subsoils. The natural occurring sand-filled cracks within these profiles provided roots with a weaker medium for growth as well as a potentially less toxic environment. However, this also limited the soil volume the vine roots were able to successfully explore and hence constrained uptake of nutrients and water (Passioura, 1991). When coupled with reduced topsoil thickness and fertility i.e. Kurosol-Scalped, root growth was further limited and vine vigour and yield were also reduced. However, root distribution was less limited when the topsoil had high levels of available nutrients and a greater thickness i.e. Kurosol-Burnt. This subsequently increased vine vigour and vine yield. Within the Kurosol-Sodic profile, the low pH of the subsoil also restricted root distribution. At this profile the high ESP and fluctuating water table of this soil are thought to have inhibited the formation of large structural cracks in which substantial root growth was observed in similar clay subsoils. Instead vine roots used prior old roots as a mechanism to avoid the low pH conditions. However this did not completely exclude the vine from adverse situations as the fluctuating watertable reduced vine root function due to periods of anaerobic conditions. Vine vigour was reduced as a result. In comparison, the Dermosol had few restrictions to root growth. Due to the upper section of this profile being derived from the dolerite colluvium the upper layers were free draining with good soil structure and high fertility. This meant that no restrictions from penetration resistance, low pH or saline watertable were observed and a large soil volume was available for root exploration. Root distribution was therefore diverse and had more efficient nutrient uptake (based on through lower root number) than within the respective Kurosol profiles. This produced highly vigorous vines that ultimately deleteriously influenced fruit yield through excessive shading.

Implications for fruit chemistry and wine quality

Fruit chemistry and wine quality analysis of vines growing at the respective profiles were undertaken by Wells (2011). This demonstrated that the differences in soil properties influenced fruit and wine composition. Within the Pinot Noir block, there was no difference in sugar level of the fruit between the Kurosol-Sodic and Dermosol profiles. However the titratable acid and juice pH were higher in fruit from the Dermosol profile. This was through increased malate concentration in fruit from the Dermosol profile, which contribute to the increase in titratable acids (Jackson, 1994). Fruit exposure to sunlight and increased temperature has also been shown to decrease titratable acids (Bergqvist *et al*, 2001; Spayed, 2002) such that the lower canopy vigour of the Kurosol-Sodic profile may have also contributed to the measured difference. There was a significant difference in the wine attributes from the two soil profiles. The juice from the Dermosol profile fermented significantly faster than juice from the Kurosol-Sodic profile. The difference in rates was correlated to the must yeast available nitrogen concentration (YAN) which was significantly higher from the Dermosol. This signifies that the vines at the Dermosol profile had greater access to nitrogen than those at the Kurosol-Sodic profile. Wines from the Kurosol-Sodic profile had a higher colour density than wines from the Dermosol profile, although the differences were not consistent between vintages. The wine from the Dermosol also had more browning due to lower levels of tannins present from increased canopy shading (Cortell and Kennedy, 2006; Joscelyne *et al*, 2007). There was also a significant difference in tannin characteristics between the wines during sensory analysis. The sensory analysis showed the wine from the Dermosol had attributes that were associated with less ripe fruit; flavours were more herbaceous and earthy compared to vegetal and red fruit characters that were present in wine from the Kurosol-Sodic profile. While different attributes were noted between the two wines, there was no difference in overall wine score. This indicates that both soils may produce significantly different wines but they may not have a perceived difference in quality.

No wine analysis was undertaken from the Sauvignon Blanc vines, however fruit chemistry analysis did show strong differences between the burnt and unburnt areas. Fruit from the Kurosol-Burnt profile had significantly lower sugar and significantly higher titrateable acids and juice pH than fruit from the Kurosol-Scalped profile. These differences were mainly caused through changes in berry weight. While the sugar concentration within the berries of the Kurosol-Burnt profile may have been lower, berry size was larger suggesting the sugar content per berry may have been similar. The higher sugar content of the Kurosol-Scalped profile indicates earlier ripening of the fruit suggesting limited water availability from this profile (Hartung *et al*, 2005; Robinson and Davies, 2000) due to the shallow topsoil, limited root exploration of the profile and lower estimated PAW within the root zone.

Implications for management of Kurosols for vineyard production

Access to sufficient rooting volume is central for adequate uptake of both nutrients and water needed for plant growth. Within the studied soils, rooting volume was restricted within all of the Kurosols due to a combination of high penetration resistance, low soil pH and occurrence of a shallow saline watertable. Therefore both physical, chemical and hydrologic restrictions to root growth occurred in these profiles. Root growth through these subsoils was only possible through the occurrence of sandy cracks and/or prior old roots which provided localised regions of favourable root growth.

Site establishment techniques that increase topsoil thickness such as mounding or ridging appear to be beneficial to vine production on these soils. Mounding not only accumulates soil and nutrients along the vine row, it also increases rooting volume and increases the moisture storage capacity of the soil. The Kurosol-Burnt and Kurosol-Scalped comparison demonstrates that increasing topsoil thickness and fertility increased root growth within these constrained subsoils, which lead to increased vine growth and fruit yield which ultimately influenced wine quality. However, if the occurrences of sandy cracks and/or prior old roots are limited within the subsoils, then mechanical creation of such areas, e.g. ripping, may be required for root penetration through the subsoil. However, due to the unstable structural conditions caused by high exchangeable Mg^{2+} and/or exchangeable Na^{+} of these subsoils, these rip-lines will be short-lived unless they can be kept open with a more stable material. Backfilling the rip-line with lime or lime amended material would be a suitable option (Spurway, 1990; Kirchhof *et al*, 1991). This would not only increase the pH of the amended area, but will also aid soil structure by displacing some of the sodium and magnesium from cation exchange sites. Amelioration of even a small section of soil (< 10% of total soil volume) via slotting and lime back filling can greatly increase yield of grapevines (Kirchhof *et al* (1991).

Conclusions

The differences in vine growth between the three profiles were related to differences in soil conditions. The hostile subsoil conditions of the Kurosol profiles restricted root distribution due to low soil pH, high penetration resistance and/or shallow water tables. Root growth within these horizons was confined to sandy cracks and prior old roots where soil penetration resistance was lower (< 2 MPa), and soil pH was potentially higher. This severely limited the volume of soil roots could access for nutrient and moisture uptake. The high concentration of roots within these small volumes of the soil lead to localised nutrient depletion around the rhizosphere meaning these roots were less able to take up nutrients compared to if they were growing in unrestrained soil. Soil profiles that allowed greater root exploration and distribution had corresponding higher pruning weights e.g Kurosol-Burnt and Dermosol profiles. At the Dermosol profile higher pruning weights occurred without a corresponding increase in root abundance suggesting that roots within this profile were more efficient in nutrient and moisture uptake, especially compared to the Kurosol-Sodic profile. This indicates that it is the efficiency of the root system that is important rather than just total root numbers.

5. Impact of soil thickness on vine growth and yield

Introduction

Soils derived from basalt are of significant economic importance to Tasmania and underpin much of the land used for intensive agriculture in the state. Such is the significance of these soil parent materials that the Red Ferrosols which form on basalt have been designated as the State soil. These soils form deep, well structured clayey profiles usually with a red or reddish-brown colour. The basalt bedrock that they are derived from was extruded as lava 10 – 50 million years ago (Seymour *et al*, 2007). While much of the volcanic activity was mainly concentrated along the NW coast, many smaller basalt flows occurred in southern region of the State. The smaller areas of basaltic soil within the southern parts of the state has meant that they have been less utilised for intensive agriculture. However there is an increasing trend for horticultural and viticultural developments.

Soil thickness and restrictive subsoils (limiting the rhizosphere) were identified as important factors in vine growth and yield within texture-contrast soils formed from Tertiary sediments (Chapter 4). This chapter aims to build on those findings and further investigate to what extent soil thickness influences root distribution on an otherwise fertile, non-saline, well structured and free draining group of soils. In this way the influence of soil depth will be examined in more detail, using a hill slope transect, without the confounding influences of waterlogging, salinity, sodicity, acid subsoils or high soil penetration resistance.

General Site description

Location

The studied site was established at Meehans Vineyard in south-eastern Tasmania located in a small valley nestled in the Meehan's Range which divides the Derwent from the neighbouring Coal River Valley (42^{o}52' S, 147^{o}25' E).

Geology and topography

The lithology underlying the study area was Tertiary basalt (Symons, 1975). The basalt was described as mugearite which has formed by volcanic crystallization of a primary magma which is dominated by the minerals oligoclase, orthoclase, pyroxene and olivine with minor apatite. This signifies that the basalt, a fine-grained basic igneous rock, was composed of oxides of aluminium and silicon as well as aluminium silicates and has impurities of calcium, sodium, potassium, magnesium, iron and phosphorus. In essence it represents a mafic, nutrient rich soil parent material, like dolerite, but finer grained, vesicular and more finely jointed. These are all features which accelerate weathering and hence soil formation.

Existing soil maps

The vineyard was covered by the Hobart 1:100,000 scale Reconnaissance Soil Map (Spandswick and Kidd, 2000a). The soils within the studied transect were mapped as a soil complex of 'Black and Red-brown soils on Basalt' (Figure 24) and are classified as either Dermosols or Ferrosols in the Australian Soil Classification (Isbell, 1996).

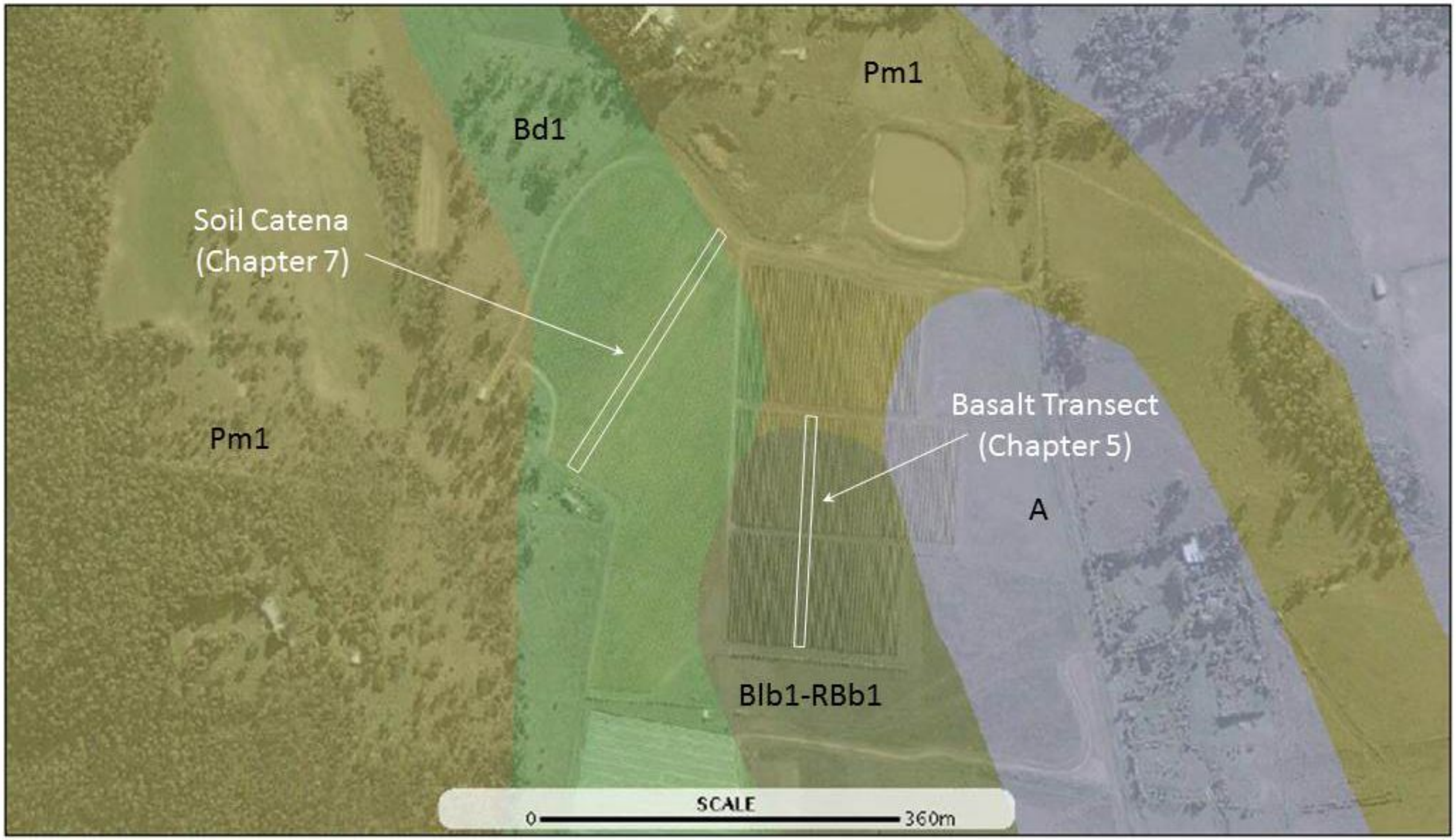

Figure 24: 1:100 000 reconnaissance soil map of the region (Spandwick and Kidd, 2000a)

Key to Soil codes:

Pm1 – Podzolics on mudstone

Bd1 – Brown soils on dolerite

Blb1-RBb1 – Black soils on basalt and red-brown soils on basalt

A – Misc alluvial soils

Individual site layout

The soil profiles in this study were located using soil-landscape features and estimates of vine vigour provided by the vineyard manager. The transect was planned to traverse the side slopes and crest of a low basalt hill. Plots were established to examine the shallow soil on the hill crest, compared with deeper soil on the side slopes (Figure 29). The vines were measured over two years, commencing in the 2006-07 season. Rows were orientated north-south with row and vine spacing of 2.5 m and 1.2 m respectively. The vines were own-rooted *Vitis Vinifera* cv Pinot Noir (clone 114) planted in 2000 and were pruned on a Scott-Henry trellis. They received similar management, including similar drip-irrigation, and were harvested on the same day each year.

Climate background at site

Monthly rainfall was determined using figures obtained from the Bureau of Meteorology weather station situated at Hobart Airport (station number 094008) which was situated 7 km to the west of the vineyard. Average rainfall for the region was 500 mm/yr with slight winter dominance although distribution is relatively consistent throughout the year. Both the 2006-07 and 2007-08 seasons had below average rainfall although rainfall during the summer months (Dec – Feb) was generally higher than normal (Figure 25). The 2005-06 season had average annual rainfall however this dominantly occurred during winter, with the remaining months receiving below average rainfall. The average maximum monthly temperature is shown in Figure 26, and shows that temperatures were consistent between the studied years. The average monthly temperature was slightly above the long-term average in all years (Table 20).

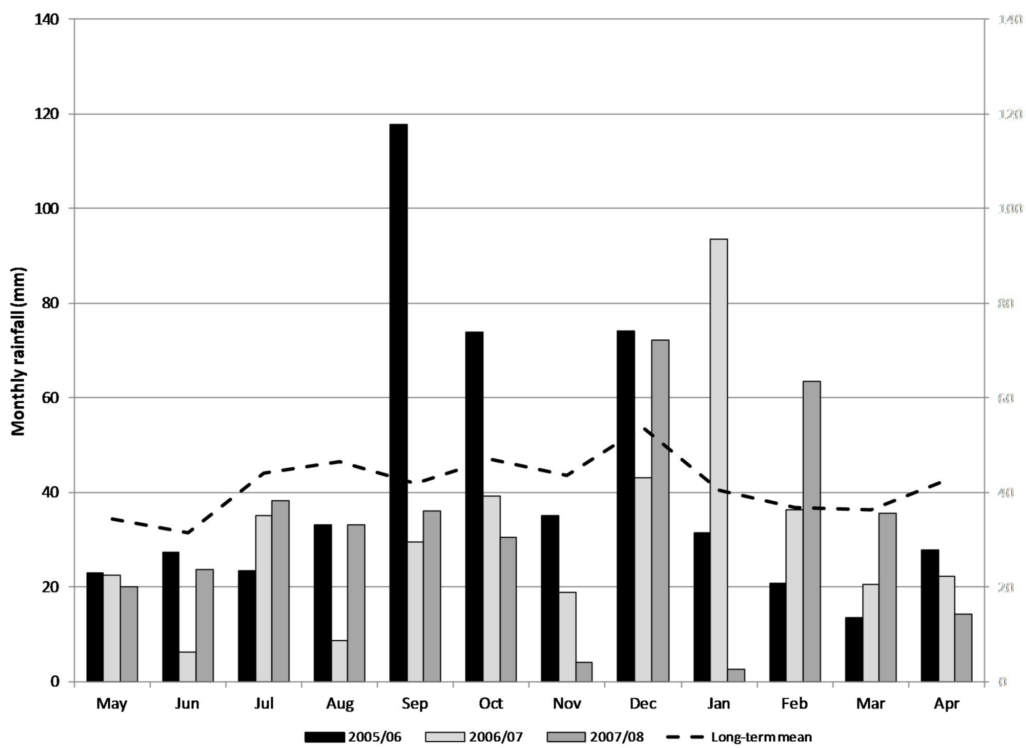

Figure 25: Mean monthly rainfall for the seasons studied and long term average (Hobart Airport, station number 094008)

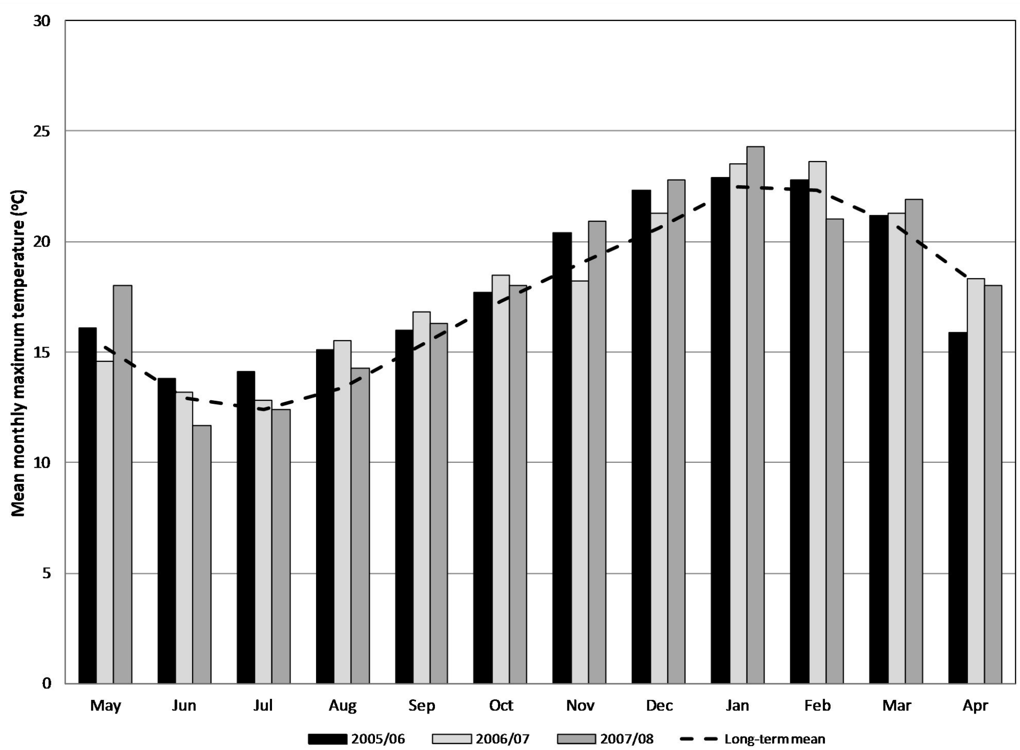

Figure 26: Mean monthly maximum temperature for the seasons studied and long term average (Hobart Airport, station number 094008)

Table 20: Annual rainfall and average monthly temperature. Data obtained from Hobart Airport (station number 094008). Long-term averages calculated from 1958 – 2011.

Season	Rainfall (mm)	Temperature (°C)
2005-06	502	18.2
2006-07	376	18.1
2007-08	374	18.3
Long-term average	500	17.5

Results

Remote sensing

The aerial vigour map shows that the plant cell density (PCD) varied across the studied vineyard blocks (Figure 27). The image shown in Figure 27 was taken in 2009 and was not used in the placement of the soil profiles. The M7 profile was located within a region of low PCD values (red) and was representative of most of the vine growth upon the hill crest. Profile M9 was located on the southern side of the hill in an area moderate to high PCD values (green/blue). The image suggested this profile's position was located in an area with slightly lower PCD values than other vines on the southern slope. Similar moderate to high PCD values were associated with the location of profile M6. However the placement of this profile was within a region of higher PCD values than other parts of the northern slope. The high PCD to the right of profile M9 corresponds to a break in slope and suggests water seepage occurs at this landscape position, a recurrent issue within this part of the vineyard (C. Surios, pers comm.)

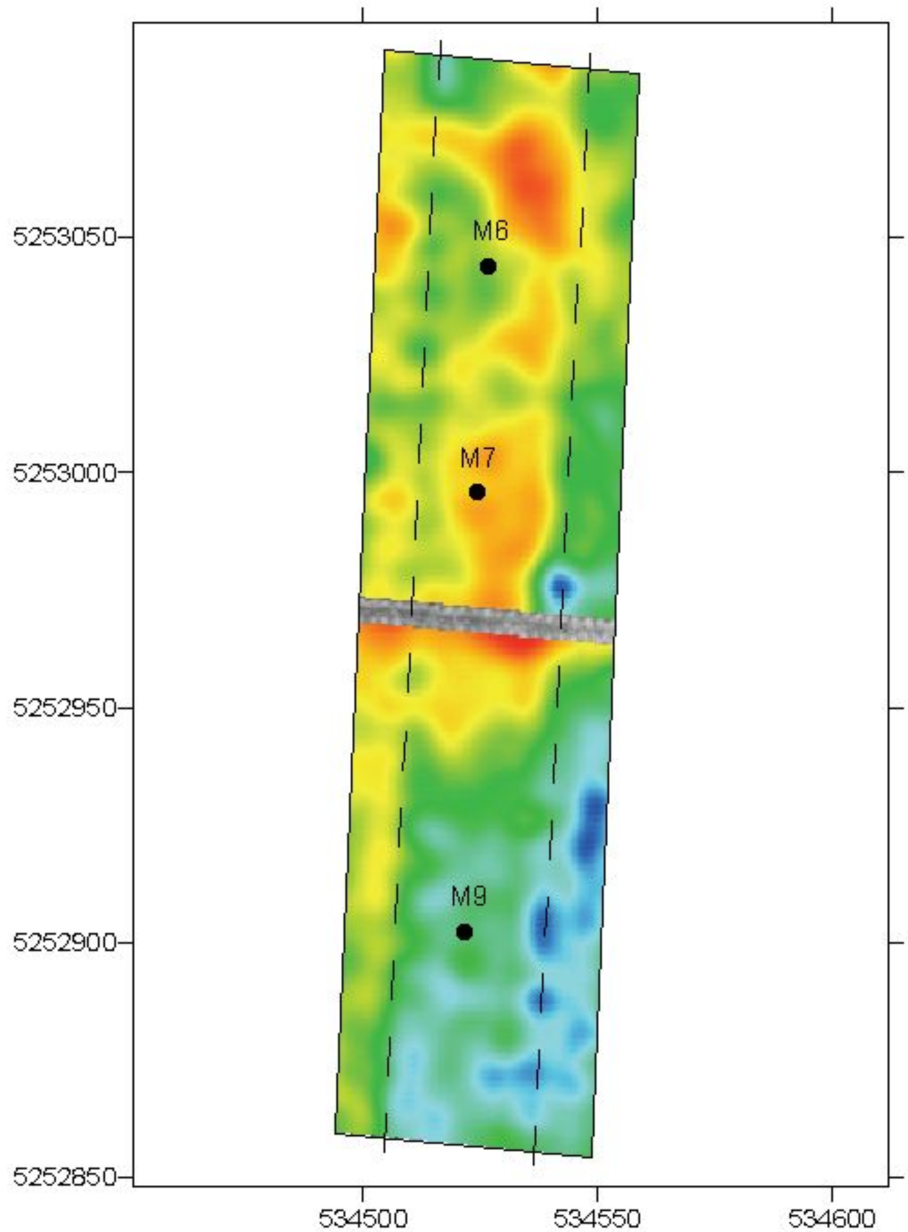

Figure 27: Infra-red image of plant cell density of the basalt transect. Blue colours indicate high plant cell density and red colours indicate low plant cell density. This image was taken in 2009. The dashed lines indicate boundaries of different vine varieties. Within the lines the variety was Pinot Noir. Vines to the left were Sauvignon Blanc and vines to the right were Riesling. The high PCD (blue) to the right of M9 signifies a break in slope and suggests water seepage within this location.

Summary soil descriptions

The studied soil profiles were all formed from vesicular, fine-grained Tertiary basalt and had similar profile morphology. All topsoils were loamy with fine polyhedral structure. This overlay clayey subsoils with moderately to strongly developed medium (10 – 20 mm) prismatic structure that parted into angular blocky peds. All profiles had common (10 – 20 %) sub-rounded and sub-angular basaltic coarse fragments (6 – 60 mm) dispersed throughout the upper soil layers. Larger coarse fragments (100 – 200 mm) were present within the lower subsoil. However these were generally less abundant (2 – 10 %). The exception to this was at profile M7 where greater frequency was observed (10 – 20 %).

A weathered basalt substrate was present beneath the soil layers in all profiles. This was more deeply weathered at both M6 and M9 profiles consisting of a yellowish brown interlocked weak gravel with a mealy consistence. The fabric of the substrate was similar at the M7 profile, however less weathering was apparent. The depth to the substrate varied between the profiles. M7 was the shallowest with less than 50 cm of soil above the weathered basalt. Profile M9 was deeper with approximately 65 cm of soil and M6 had the greatest depth of soil of approximately 90 cm.

Both the M6 and M7 profiles were classified as Haplic, Eutrophic Red Ferrosols (Isbell, 1996, see Table 21) whereas the M9 profile was darker and classified as a Haplic, Eutrophic Brown Dermosol.

Table 21: Soil Classification summary

Soil Profile	Order	Suborder	Great Group	Subgroup	Family criteria					
					A horizon thickness	Gravel (surface and A1)	A1 Horizon texture	Max clay content of B horizon*	Soil depth	Slope angle (%)
M6	FE	AA	AH	CD	B	F	L	O	V	8
M7	FE	AA	AH	CD	B	F	L	O	U	2
M9	DE	AB	AH	CD	B	F	L	O	V	7

*estimated from field texture

Key to Classification codes:

AA – Red

AB – Brown

AH – Eutrophic

CD – Haplic

DE – Dermosol

FE – Ferrosol

A – Thin (< 0.1 m)

B – Medium (0.1 – 0.3 m)

C – Thick (0.3 – 0.6 m)

F - Slightly gravelly (2 – 10 %)

L – Loamy (SL-L, 10 – 20 % clay)

O – Clayey (LC-MC-HC, > 35 % clay)

U – Shallow (0.25 - < 0.5 m)

V – Moderate (0.5 - < 1.0 m)

Figure 28: Basalt transect soil profiles. a) M6 (north aspect); b) M7 (shallow); and c) M9 (south aspect). The strong fine-medium sized prismatic structure of the B21 can clearly be seen between 25 – 40 cm in all profiles. An example of a clay vein within the substrate can be seen as a diagonal grey band within the substrate of profile M6 (a) (arrowed).

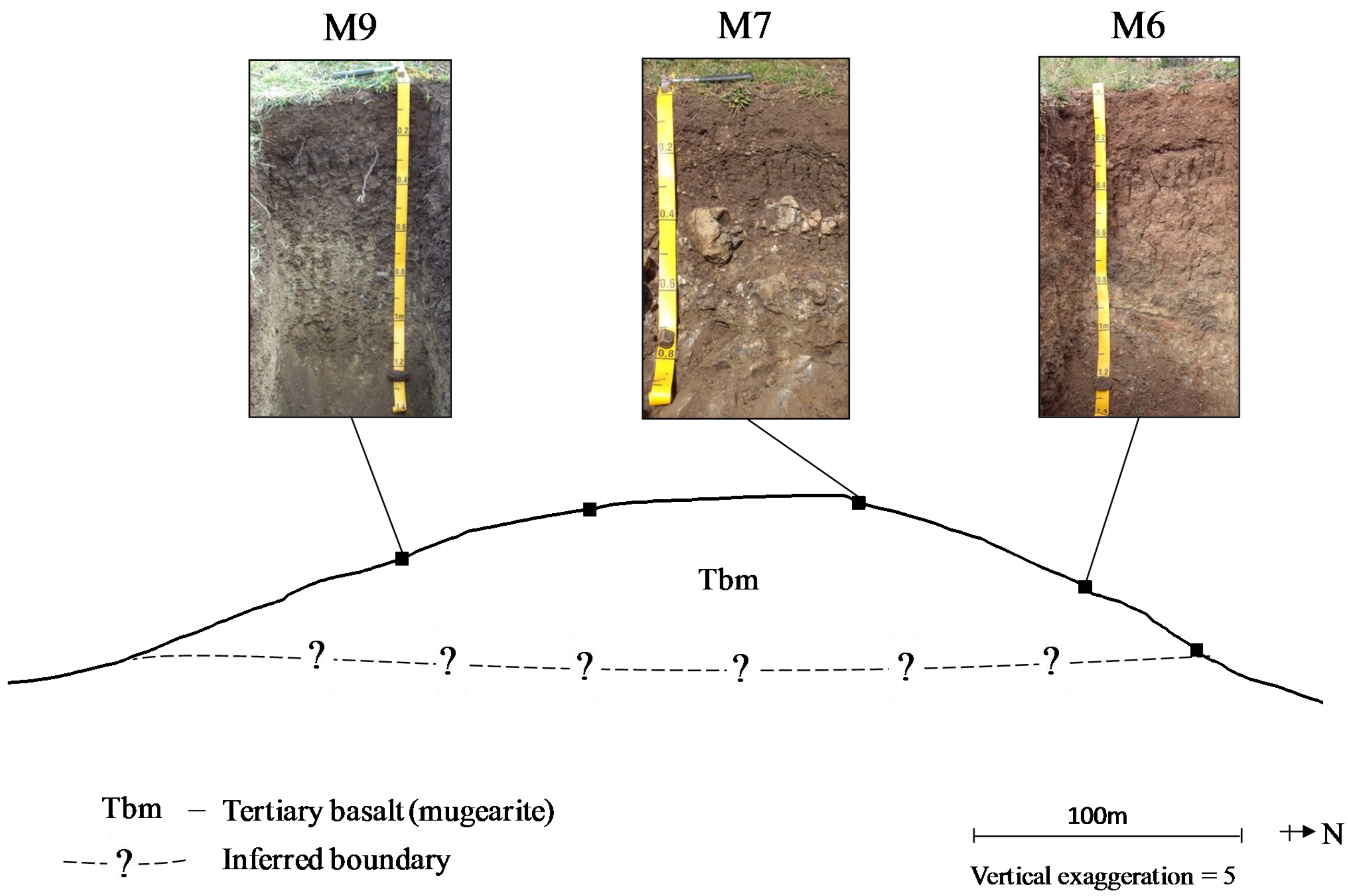

Figure 29: Location of soil profiles in relation to landform, aspect and geology

Table 22: Summary of key profile features

Horizon	Depth (cm)	Matrix Colour (moist)	Texture	Structure Primary				Secondary			Consistence
M6											
A11p	0 – 9	5YR 4 4	L	S	f	PO	+	M	m-f	PO	weak
A12	9 – 28	5YR 4 4	CL	S	m-f	PO	->	M	f	PO	weak
B21	28 – 59	5YR 4 4	LC	S	m	PR	->	S	m-f	AB	firm
B22	59 – 91	5YR 5 3	LC	M	m	PR	->	M	m	AB	firm
BC	91 – 145+	7.5YR 5 3	SCL	W	m	PO					firm
M7											
A11p	0-12	5YR 4 4	L	S	f	PO	+	M	m-f	PO	weak
A12	12-34	5YR 4 4	CL	S	m-f	PO	->	M	f	PO	weak
BC	34-47	5YR 4 5	CL	S	m	PR	->	S	m-f	AB	firm
C	47-80+										
M9											
A11p	0-4	7.5YR 4 4	L	S	f	PO	+	M	m-f	PO	weak
A12	4-23	7.5YR 4 3	CL	S	m-f	PO	->	M	f	PO	weak
B2	23-51	7.5YR 5 3	LC	S	m	PR	->	S	m-f	AB	firm
BC1	51-64	7.5YR 5 3	LC	M	m	PO	->	W	f	PO	firm
BC2	64-85	7.5YR 5 4	SCL	W	m	PO					firm
BC3	85-140+	7.5YR 5 4	SCL	W	m	PO					firm

See Appendix 1 for a description of codes

Soil analysis

The soil chemistry of the three soil profiles was very similar (Table 23 & Figure 30) and overall the sites had ideal soil chemical characteristics. Electrical conductivity (EC) was low throughout all profiles with values generally less than 0.2 dS/m. A slight increase in EC was measured within the subsoil at M7 however this was not substantially higher than values measured from the other two profiles. Soil pH was virtually identical between the profiles and demonstrated all were slightly acidic and had a slight alkaline trend with depth. Only the topsoils showed any difference in soil pH with M7 being more acidic than either M6 or M9 (pH_{CaCl_2} of 5.5 compared to 5.9 and 6.3 at M6 and M9 respectively). Very little difference in organic carbon was observed between the respective profiles. Highest values of organic carbon were measured in the topsoil horizons (3.7 – 3.9 % OC) with values then declining with depth.

All profiles had abundant exchangeable cations. The trends for exchangeable Mg^{2+}, exchangeable Na^{+} and exchangeable K^{+} were all similar between the profiles. Exchangeable Mg^{2+} and exchangeable Na^{+} increased with depth until the subsoil horizons where values remain consistent. In both cases, profile M7 had slightly higher values within the topsoil than the other two profiles. The low values of exchangeable Na^{+} resulted in no sodicity present at any profile, with the exchangeable sodium percentage (ESP) less than 6 % for all soil horizons (ESP generally < 2 %). Exchangeable K^{+} declined with depth in all profiles and while trends were similar, profile M7 had lower values within the topsoil and M9 had slightly higher subsoil values. The greatest difference between the three profiles occurred in exchangeable Ca^{2+}. Both M6 and M7 profiles had similar trends of exchangeable Ca^{2+} with high values throughout the profile (> 20 cmol(+)/kg). At M9 however, exchangeable Ca^{2+} values were lower throughout the soil horizons (< 50 cm) with values generally less than 15 cmol(+)/kg.

However, the weathered substrate of this profile had exchangeable Ca^{2+} consistent with the other profiles. The A11p of both M6 and M9 profiles showed increased exchangeable Ca^{2+} compared to the underlying A12 horizon. This corresponded to increases in soil pH in these horizons. Analyses of the clay veins indicate that the chemistry was somewhat similar to the substrate of each profile (Table 23). However these regions had higher ECEC as well as slightly higher exchangeable Ca^{2+} and exchangeable Mg^{2+} than the surrounding weathered substrate.

Table 23: Selected soil chemistry analysis.

Horizon	Depth (cm)	pH (1:5) CaCl₂	pH (1:5) H₂O	EC (dS/m)	Exchangeable Cations (cmol(+)/kg) Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	ECEC	ESP (%)	Org C (%)
M6											
A11p	0 – 9	5.9	6.0	0.21	26.9	2.1	0.3	1.4	30.6	1.0	3.9
A12	9 – 28	5.5	6.0	0.10	21.6	2.3	0.4	0.6	24.9	1.6	3.5
B21	28 – 59	6.1	6.6	0.09	31.6	8.9	0.6	0.2	41.3	1.5	1.5
B22	59 – 91	6.2	6.8	0.10	21.9	6.7	0.6	0.1	29.3	1.9	0.8
BC	91 – 145+	6.6	7.4	0.10	18.8	14.3	0.6	0.1	33.8	1.7	0.6
Clay vein	59 – 67	6.7	7.3	0.12	22.6	16.7	0.6	0.1	40.0	1.4	
Clay vein	80 – 91	6.5	6.9	0.15	22.1	15.6	0.6	0.1	38.4	1.6	
M7											
A11p	0-12	5.5	5.9	0.18	22.4	4.2	0.2	0.5	27.4	0.9	3.7
A12	12-34	5.5	5.6	0.11	28.3	9.1	0.6	0.1	38.2	1.7	3.4
BC	34-47	5.8	5.6	0.20	26.2	9.3	0.6	0.1	36.3	1.8	1.9
C	47-80+	6.0	6.1	0.19	23.5	5.2	0.7	0.2	29.5	2.2	1.5
Clay vein	63-69	5.9	6.0	0.19	27.6	11.2	0.7	0.2	39.6	1.7	
M9											
A11p	0-4	6.3	6.3	0.14	17.5	2.0	0.2	1.1	20.8	0.9	3.8
A12	4-23	5.6	5.8	0.07	12.0	2.4	0.2	0.4	15.0	1.1	3.5
B2	23-51	6.0	6.0	0.06	13.9	8.6	0.4	0.3	23.3	1.9	1.6
BC1	51-64	6.2	6.2	0.05	21.4	8.8	0.4	0.4	31.1	1.4	0.7
BC2	64-85	6.3	6.4	0.03	18.9	7.9	0.5	0.3	27.6	1.7	0.6
BC3	85-140	6.5	6.6	0.03	15.9	8.3	0.4	0.3	24.9	1.8	3.8
Clay vein		6.4	7.0	0.10	24.0	12.6	0.8	0.3	37.7	2.0	

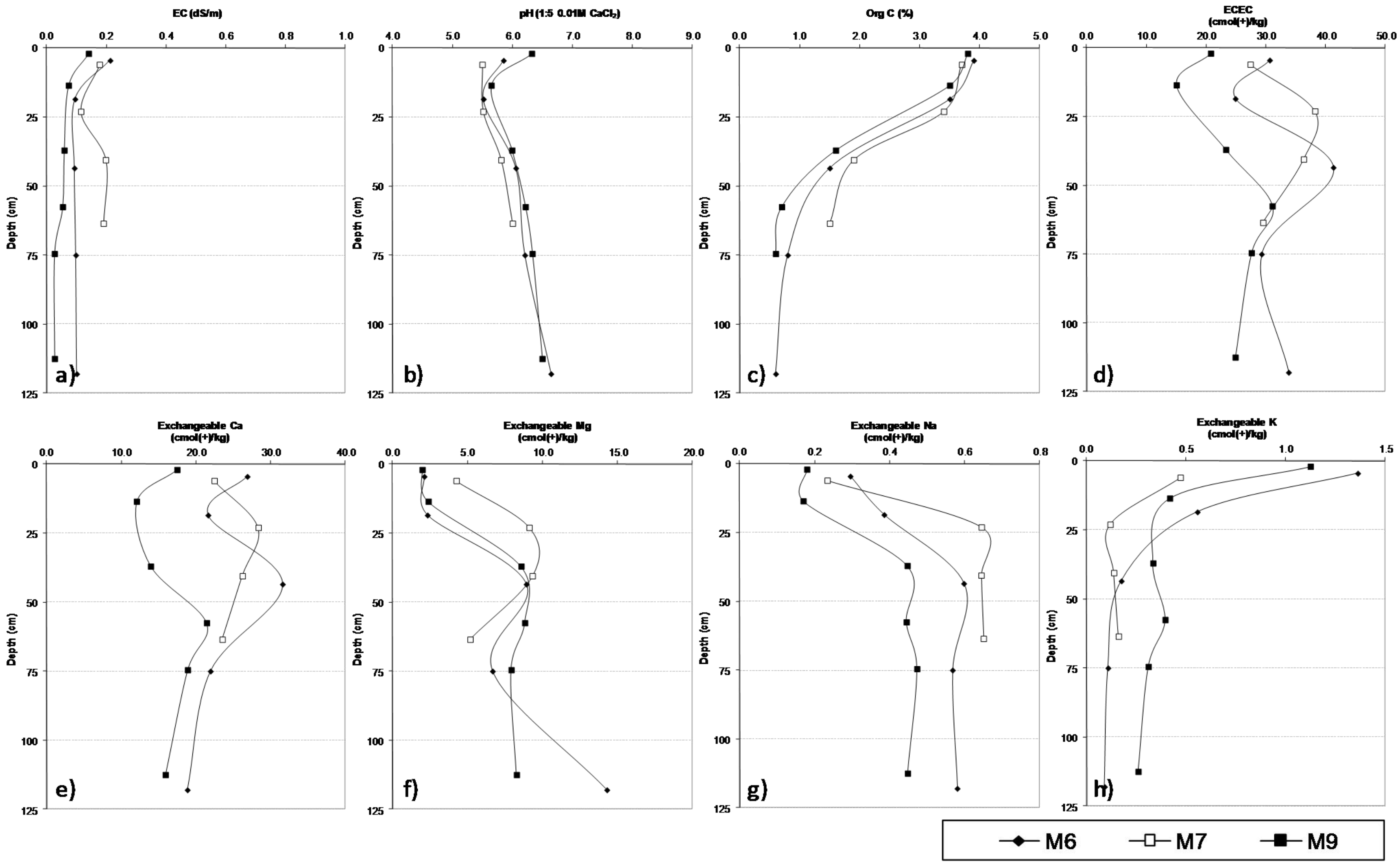

Figure 30: Combined soil chemistry of the profiles at Basalt transect. All soil profiles had similar soil chemistry with only M9 having slightly lower exchangeable Ca^{2+} (e) and exchangeable Na^{+} (g)

Root Distribution

Substantially fewer roots were measured at profile M7 than at either profiles M6 or M9 (Table 12). M7 had less than half the total root number of the other two profiles (933 roots at M7 compared to 2453 and 2567 for M6 and M9 respectively). The proportion of both fine (< 1mm) and medium roots (1 – 2 mm) was also contrastingly different at profile M7. At this profile the proportion of fine roots was lower than the other two profiles (62.6 % compared to 75.7 % and 76.3 % at M6 and M9 respectively) whereas the percentage of medium roots was higher (30.2 % compared with 18.8 % and 17.7%). No coarse roots (> 5 mm) were observed at profile M7, whereas a both M6 and M9 had occurrences of this root size although the proportion was low at both profiles (< 1 % of all observations).

All profiles had highest root abundance in the upper 10 – 40 cm of soil with root numbers then declining with depth (Figure 31). Very limited numbers of root observations occurred in the upper 0 – 5 cm of all soil profiles. Although the root growth at both M6 and M9 was quite similar, slight differences in distribution were observed. This was particularly the case for the 1 – 2 mm root where M6 had lower abundance of these roots within the topsoil when compared to M9. However this was offset by an increase in abundance at depth, resulting in the two profiles having almost identical occurrence of 1 – 2 mm roots (462 observations at M6 compared to 455 at M9). The higher root growth at depth of M6 was not restricted to just the one root size, with both the < 1mm and 2 – 5 mm size classes also having increased root abundance at similar depths. In all cases the increased subsoil root growth was associated with the clay veins that occurred within the substrate. This association can be clearly observed as a linear feature within the subsoil in Figure 31a. Roots were also observed within clay veins at both M7 and M9 profiles however the growth was not as prolific as at profile M6. Within the M7 profile, zones of increased root growth were also observed at A11p/A12 boundary (approximate depth of 10 cm) as well as at the base of the B2 (35 – 40 cm).

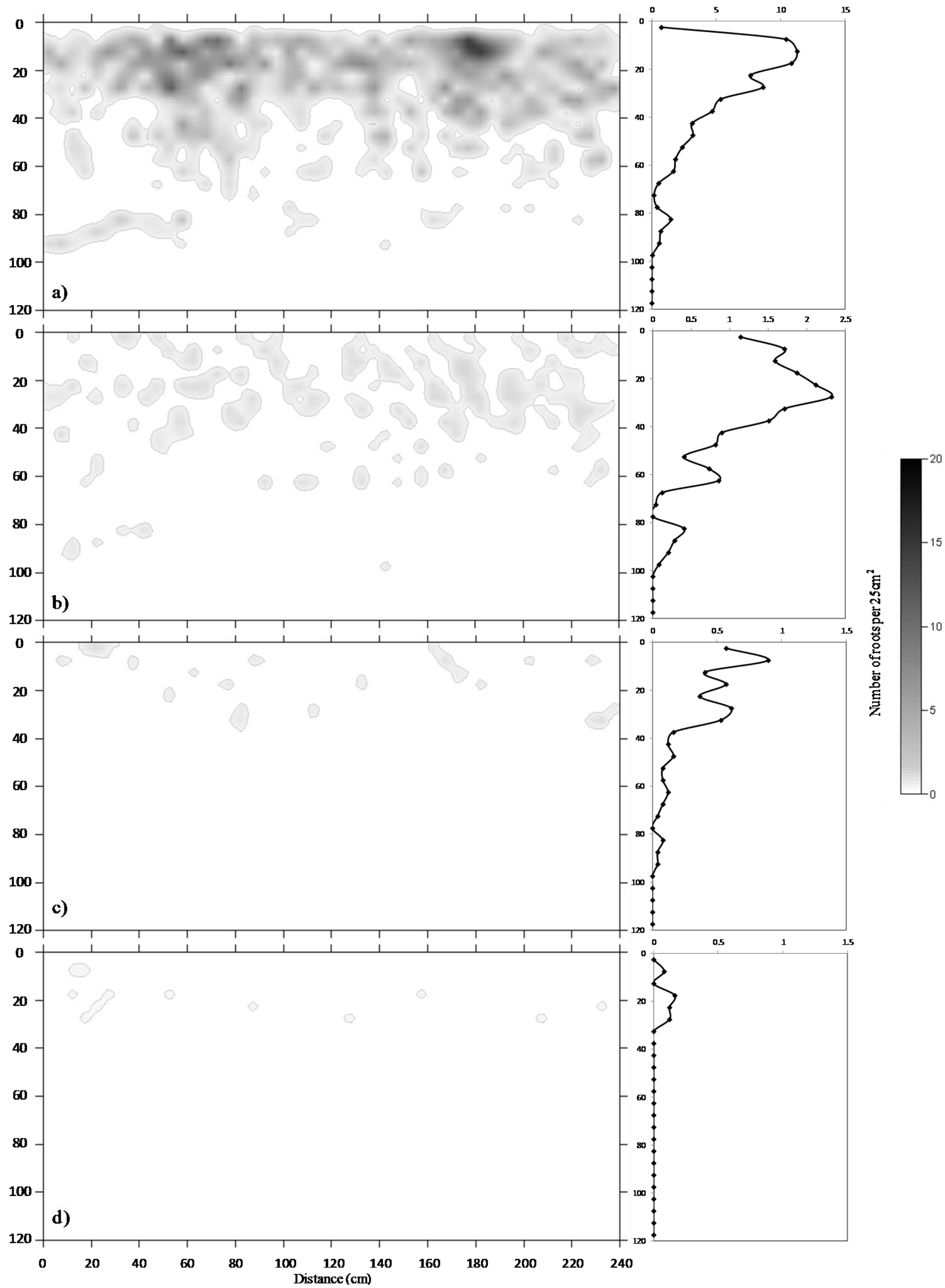

Figure 31: Root distribution for the basalt profile M6 (Basalt - north) showing the distribution of the following diameter classes: a) < 1mm; b) 1 – 2 mm; c) 2 – 5 mm; d) > 5 mm. Darker shading indicates higher root density. The right-hand graph shows the percentage of total roots for each size class with depth. Note: the scale for < 1 mm root class is six times greater than the other classes.

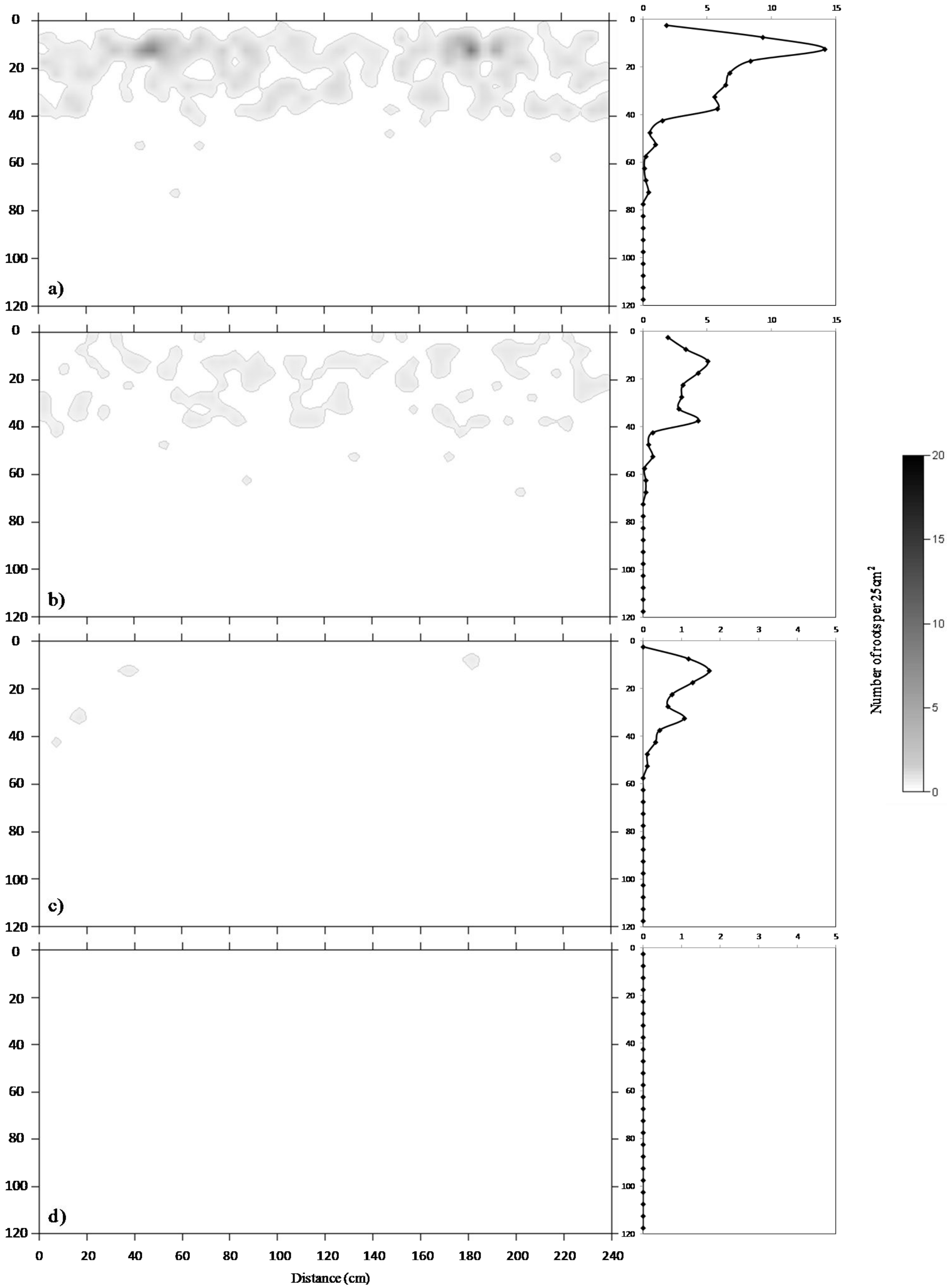

Figure 32: Root distribution for the basalt profile M7 (Basalt - shallow) showing the distribution of the following diameter classes: a) < 1mm; b) 1 – 2 mm; c) 2 – 5 mm; d) > 5 mm. Darker shading indicates higher root density. The right-hand graph shows the percentage of total roots for each size class with depth. Note: the scale for 2 - 5 mm & > 5 mm root classes are three times less than the other classes.

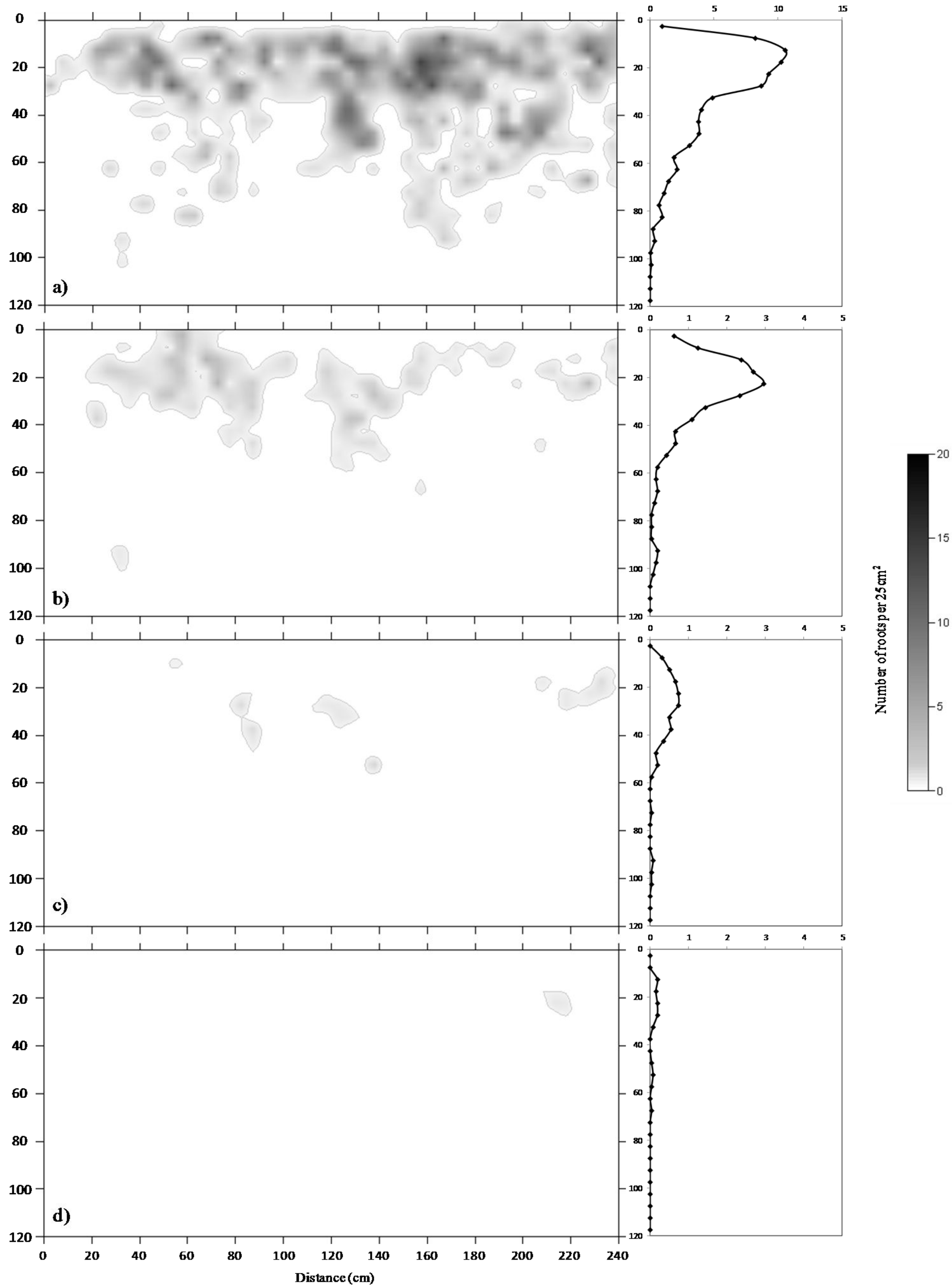

Figure 33: Root distribution for the basalt profile M9 (Basalt - south) showing the distribution of the following diameter classes: a) < 1mm; b) 1 – 2 mm; c) 2 – 5 mm; d) > 5 mm. Darker shading indicates higher root density. The right-hand graph shows the percentage of total roots for each size class with depth. Note: the scale for < 1 mm root class is three times greater than the other classes.

Root numbers with depth for the different root size classes

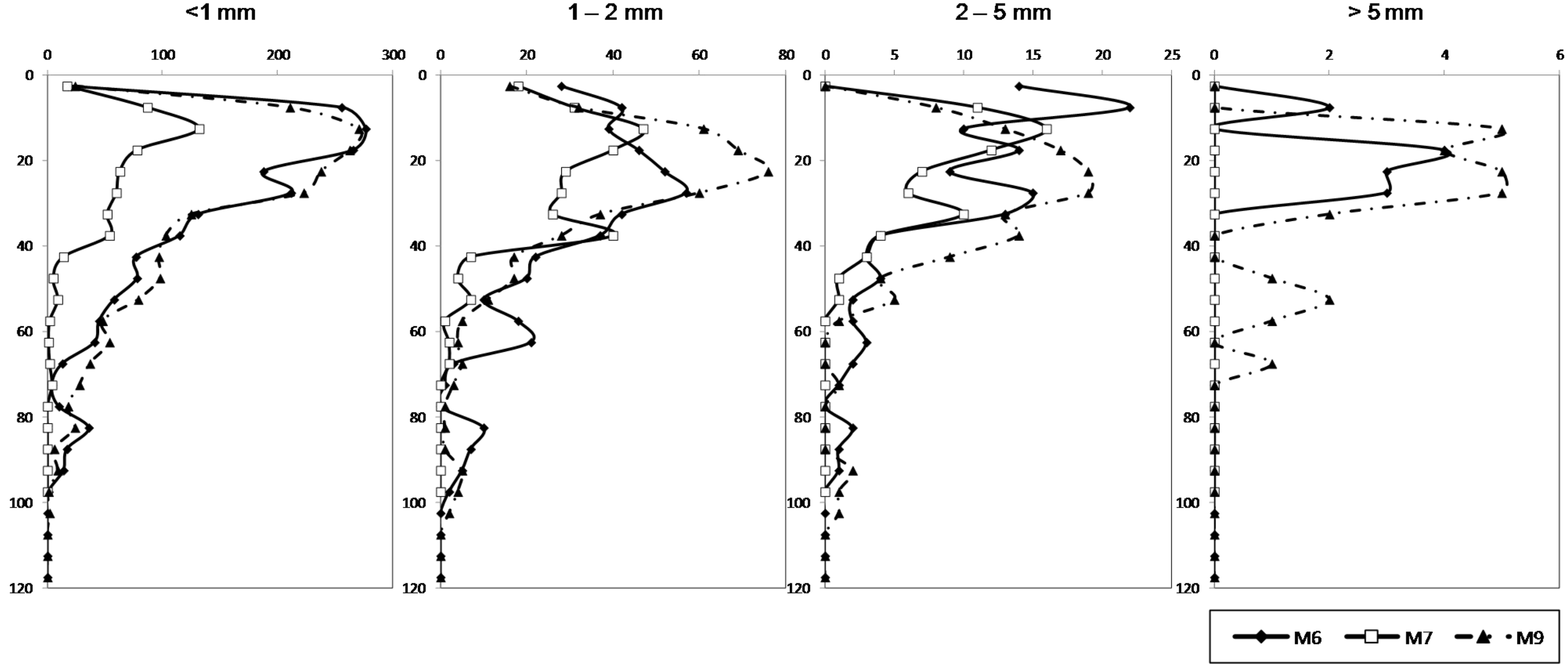

Figure 34: Root numbers with depth at the Basalt transect. The shallow profile (M7) had substantially less fine (< 1 mm) and medium (1 – 2 mm) roots throughout the entire profile. No coarse roots were observed within M7.

Table 24: Total root numbers for the respective Basalt soil profiles. Numbers in brackets indicate the percentage of the total root observations for each profile.

	Root numbers				
	< 1mm	**1-2 mm**	**2-5 mm**	**> 5mm**	**Total**
M6	1857 (75.7)	462 (18.8)	122 (5.0)	12 (0.5)	2453 (100)
M7	580 (62.6)	282 (30.2)	71 (7.6)	0 (0.0)	933 (100)
M9	1959 (76.3)	455 (17.7)	127 (4.9)	26 (1.0)	2567 (100)

Estimation of Plant Available Water

The estimated values of plant available water (PAW) using the upper 1 m of the soil profile reflected the obvious differences in soil depth (Table 25). The deepest profile (M6) had the highest PAW estimation and the shallowest profile (M7) had the lowest estimated PAW.

The similarities between M6 and M9 in root distribution resulted in comparable estimations of PAW within the effective root zone (90 % of root observations). The shallow root distribution of the M7 profile however, resulted in this profile having a lower estimation of PAW within the effective root zone than the other two profiles.

Table 25: Estimation of plant available water (PAW)

Profile	PAW (1 m depth) (mm/m)	Depth of 90% root observations (cm)	PAW (90 % roots) (mm)
M6	119.3	52.5	70.4
M7	69.3	35	50.7
M9	81.0	52.5	68

Multivariate analysis of root distribution

The two-factor loading plots describing analysis of root distribution and penetration resistance are shown in Figure 35. These plots account for approximately half of the variation in roots observed within the different profiles (56.1 %, 56.7 % and 56.0 % for M6, M7 and M9 respectively). These plots indicate that root occurrence is negatively correlated with soil depth as the respective root sizes are opposed to depth on each loading plot. This was also reflected in negative correlation coefficients between all root sizes and depth (Table 26). All profiles had strongest correlations between the fine roots (< 1mm) and depth with correlations coefficients decreasing as root size increased. The correlation coefficients between depth and each respective root size were similar for each profile.

Strong correlation coefficients were also observed between the different root size classes indicating that roots had a tendency to grow together. This was also demonstrated on the loading plots by the individual root sizes being located close to each other. The correlation between the root classes were similar at profiles M6 and M9, however stronger correlations were recorded at M7. While the correlations between root sizes were similar at M6 and M9, there was a difference in clustering on the respective loading plots. This was most likely due to the different correlations of the root sizes and depth recorded at this profile.

Table 26: Pairwise correlations coefficients of respective root size classes and soil position of the Basalt transect.

Indices		Correlation coefficient M6	M7	M9
< 1 mm	Distance	-0.1652	-0.0965	-0.0805
< 1 mm	Depth	-0.5781	-0.4958	-0.5284
1-2 mm	Distance	-0.0604*	-0.0003^{n}	-0.0522^{n}
1-2 mm	Depth	-0.4052	-0.4340	-0.3939
1-2 mm	< 1 mm	0.4627	0.5480	0.4312
2-5 mm	Distance	-0.0163^{n}	-0.0390^{n}	0.0545^{n}
2-5 mm	Depth	-0.2899	-0.2641	-0.2569
2-5 mm	< 1 mm	0.3726	0.4586	0.3516
2-5 mm	1-2 mm	0.4050	0.4184	0.4147
> 5 mm	Distance	0.0388^{n}	-	0.0661*
> 5 mm	Depth	-0.1209	-	-0.1311
> 5 mm	< 1 mm	0.0853	-	0.1506
> 5 mm	1-2 mm	0.0137^{n}	-	0.1985
> 5 mm	2-5 mm	0.1311	-	0.1897

All values are significant (P<0.001) except were indicated with 'n' or '*' which refer to no significance and P<0.05 respectively. No > 5 mm roots were observed at M7. Note: penetration resistance was not measured at these profiles.

Depth = vertical depth from soil surface

Distance = horizontal distance from vine trunk

< 1 mm, 1-2 mm, 2-5 mm & > 5 mm = respective root size classes

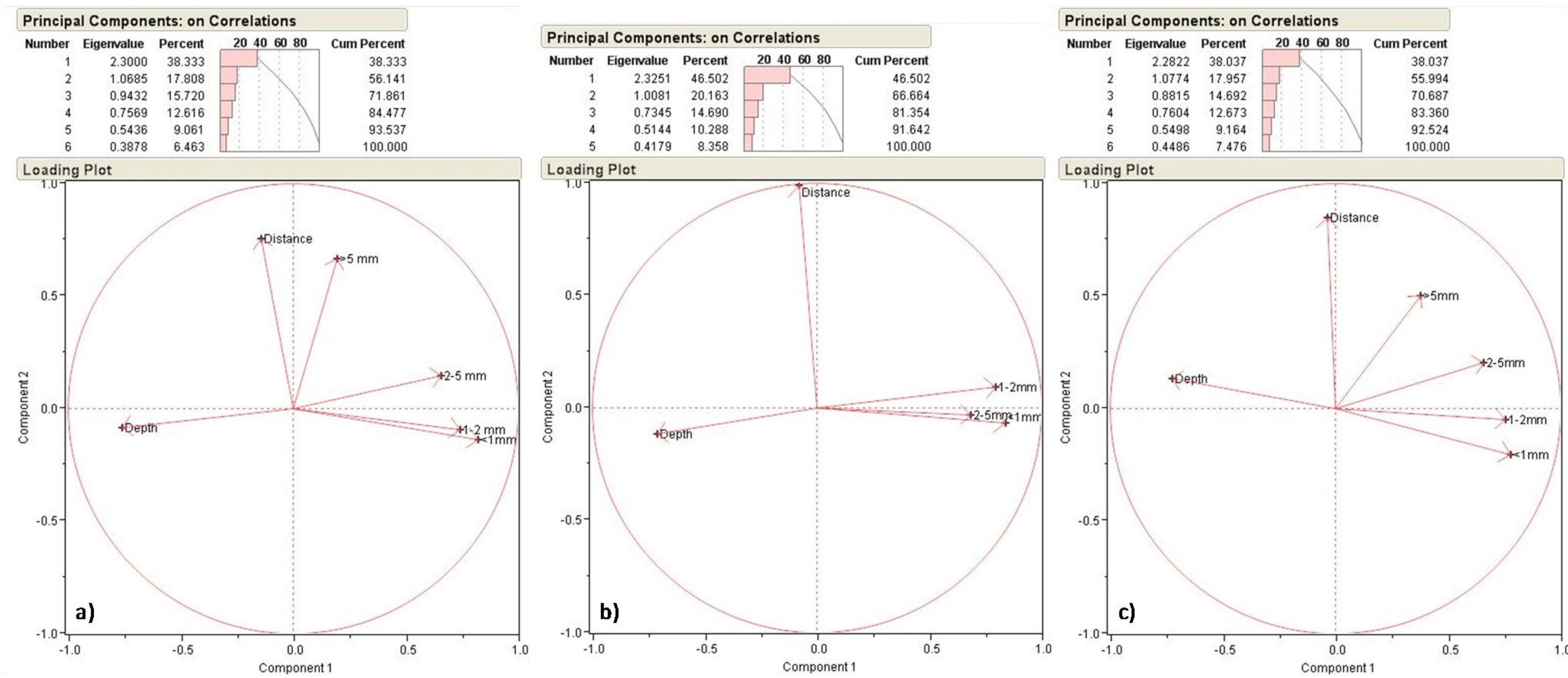

Figure 35: Two-factor loading plots of root size class and soil position,
Soil profiles are a) M6 (north aspect); b) M7 (shallow); and c) M9 (south aspect)

Vine measurements

Profile M7 had significantly lower ($P < 0.05$) pruning weight and fruit yield than the other two profiles (Table 27). Average pruning weight at M7 was below 1.3 kg/vine in both years compared to M6 and M9 that both had average pruning weights greater than 1.5 kg/vine each year. The difference in pruning weight occurred through differing cane weights as there was no statistical difference in shoot numbers between the profiles in any year. The average cane weight at M7 was approximately 55 – 60 grams per cane. This was significantly lower ($P < 0.05$) than the other profiles which both had average cane weight of approximately 80 grams per cane. In 2008 however the average cane weight at M6 was also significantly lower than M9 (61.9 g/cane compared to 77.5 g/cane) making the average cane weights of all profiles significantly different in that year.

The trend for fruit yield reflected that of vigour with M7 significantly lower ($P < 0.05$) yielding than M6 and M9 in each season. No significant difference in yield was measured between M6 and M9 in any year. Bunch number was not significantly different between profiles in any year, however all profiles showed an increase in bunch number between 2007 and 2008. Bunch weight was significantly lower at M7 with an average bunch weight of 85 – 95 grams per bunch compared to 130 – 140 grams per bunch at both M6 and M9. While individual berry weight was not recorded, the berries at M7 were visually smaller than the other two profiles.

The respective yield to pruning weight ratios (Y:PW) remained relatively consistent between the profiles each year. Most Y:PW were low (< 2.5) with only M6 having a value higher than this in 2008 (Y:PW of 2.7).

Table 27: Vine measurement data from the Basalt profiles. Different letters indicate parameter values are significantly different ($P < 0.05$) between profiles in that year.

Parameter	Year	M6	M7	M9
Av. Yield:Pruning	2007	2.33 b	2.09 a	2.23 b
weight ratio	2008	2.73 a	2.43 ab	2.35 b
Av. Yield	2007	3.49 a	2.27 b	3.52 a
(kg/vine)	2008	4.07 a	3.04 b	4.18 a
Av. Bunch Number	2007	26.99 a	26.76 a	27.09 a
(bunches/vine)	2008	29.25 a	31.83 a	29.34 a
Av. Bunch weight	2007	129.3 a	95.6 b	129.9 a
(g)	2008	139.0 a	84.8 b	142.6 a
Av. Pruning weight	2007	1.50 a	1.09 b	1.58 a
(kg/vine)	2008	1.49 b	1.25 c	1.78 a
Av. Shoot number	2007	18.42 a	18.63 a	18.42 a
(shoots/vine)	2008	24.08 a	23.92 a	23.58 a
Av. Cane weight	2007	81.76 a	58.58 b	85.83 a
(g)	2008	61.87 b	53.25 c	77.51 a

Discussion

Soil properties and soil formation

The three studied soil profiles had many similar properties which support the idea they are formed directly from the weathering basalt. All profiles had similar soil pH, EC, organic carbon, high ECEC and low ESP. The basalt parent material was described as mugearite indicating that the chief minerals were oligoclase with associated orthoclase, olivine and minor apatite. Oligoclase and orthoclase are primarily aluminium silicates with impurities of calcium and sodium (oligoclase) or potassium (orthoclase) and olivine is a combination of iron and magnesium silicates. Therefore the weathering of these minerals has helped to produce the high levels of exchangeable cations observed within the profiles. All soils appear to be highly fertile with no salinity or pH restrictions based on the measured attributes.

Soil structure was also similar with all profiles having friable granular topsoil horizons overlying prismatically structured subsoils. The similarity in soil structure is clearly evident in Figure 28. The strong structural aggregates are attributed to the presence of iron oxides as indicated by reddish brown matrix colours which is derived from the weathering basalt. Iron oxides are known to be important aggregate cementing agents and have close association with soil organic matter. The high levels of organic carbon of these profiles (> 3 % within all topsoils) suggest that iron oxide levels are also likely to be high, although not measured, and these levels of organic carbon occur despite the droughty, shallow and rocky nature of the site.

The greatest difference between the profiles was total soil thickness in which M7 had a shallower depth to the weathered substrate than either M6 or M9. This in turn suggests soil colluvium and/or slope wash has moved from the top of the hill (M7) and accumulated on the side slopes (M6 and M9). This was confirmed through the presence of *in situ* clay veins through the substrate that are abruptly truncated at the soil-substrate boundary. The presence of fine (< 1 mm) clasts of weathered basalt indicates that these clay veins have been intruded into the basalt substrate rather than being formed in place (S Forsyth, pers comms). The rounded coarse fragments within the subsoil are further evidence that the solum is colluvial material as these were present without any corresponding weathering into the surrounding soil i.e. floaters with minimal weathering rinds. As soil texture and soil horizons were similar between the profiles, it is likely that the colluvium moved through creep and other mass movement processes from the upper slopes rather than fluvial erosion and deposition of surface soil. The porous and well structured soil with open fractured substrate is likely to generate very low levels of horizontal overland flow. All profiles showed evidence of soil movement demonstrating that even the soil on top of the hill crest had some re-working. Therefore, while the soil profiles were strongly related to the underlying bedrock the soil had not formed entirely *in situ*. This has important implications for understanding the occurrence of soil materials in the landscape.

While all soils were closely related, slight differences did occur in soil chemistry between the profiles. The largest variation was recorded in levels of exchangeable Ca^{2+} with substantially lower values within the soil layers (< 50 cm) at profile M9. The southerly aspect of this profile meant it has less exposure to direct sunlight than the other profiles and potentially had increased soil moisture that allowed dissolution and leaching of calcium within the profile. The darker colour of this profile is consistent with increased moisture content, reducing the amount of free iron-oxide. Increased water movement through this profile would also explain the lower exchangeable Na^{+} within M9 compared to the other profiles. Profile M6 also had lower exchangeable Na^{+} than M7, particularly within the soil horizons (< 60 cm), however values were still higher than at M9. This suggests that both M6 and M9 have increased water flow compared to M7. This is reflected in the EC of the respective profiles with M7 having highest EC throughout the profile and lowest EC at M9. The position of M7 on the hill crest may lead to greater water shedding by both surface flow and sub-surface lateral flow due to the convex, maximal landscape position. It is likely that the fractured and highly permeable weathered substrate allowed water flow from the hill crests to flow rapidly to the surrounding slopes as seepage at these locations, as reported by the vineyard manager (C.

Surios, pers comm.). As M9 had lower exchangeable Na^{+} than M6 it is suggested that substantial subsurface lateral water flow occurs in a southerly direction, towards M9.

Profiles M6 and M9 both had an increase in exchangeable Ca^{2+} within the surface horizon. While this could be in part due to lime application, the lack of a corresponding increase at profile M7 suggests that it may also be due to topsoil movement downslope from M7.

Influence of soil properties on root growth and distribution

Highest root abundance occurred in the top 10 – 40 cm of all soil profiles with root numbers then declining with depth. The slight differences in soil chemistry were not responsible for the root distribution observed between the profiles. This was concluded as the M9 profile had the greatest differences in soil chemical properties but had similar high root growth as the M6 profile. This demonstrates that the lower exchangeable Ca^{2+} at profile M9 was non-limiting to root growth. Instead differences in root growth were attributed to differing soil thickness and assumed moisture holding capacity of the profiles.

The shallower soil thickness of M7 resulted in substantially less roots at this profile. Almost all of the roots were contained within the upper 40 cm of soil with very few roots recorded below this depth. This contrasted with both M6 and M9 profiles which had greater soil thickness and higher root numbers (approximately 2.5 times higher total root numbers than at M7). Along with having similar total root number, the M6 and M9 profiles also had similar proportion of roots within the respective root size classes (Table 12). However, the M7 profile not only had substantially fewer roots but it also had a substantially lower proportion of fine roots (< 1 mm) and higher proportion of 1 – 2 mm roots than the other soils. In all profiles, the proportion of fine roots was much lower when compared to the soil profiles studied in other chapters indicating that the basalt profiles had a different influence on root growth. In the previous chapters, an increase in fine root proportion was associated with increased restriction to root growth. It is therefore feasible that the lower percentage of fine roots within the basalt soils indicate

less root restriction throughout the soil profile as all the basaltic soils had friable, well structured profiles. However, this does not explain the low proportion of fine roots at the shallow M7 profile. Anderson *et al* (2003) concluded that fine roots had a shorter lifespan and increased turnover than coarse roots. Root growth and survival is expected to be higher during periods of favourable soil moisture (Conradie, 2002). However the shallow soil profile and fractured, highly permeable substrate of M7 was thought to limit the moisture holding capacity of this profile making the root zone prone to fluctuations in soil moisture. Large roots can only develop if the smaller roots have access to sufficient periods of favourable soil moisture. In drier years the larger roots have greater resilience to desiccation and thus are more likely to survive periods of low soil moisture, leading to greater abundance of larger roots. Within profile M7 the regions of highest root growth corresponded to the boundaries between horizons. These regions have increased moisture due to the textural and structural differences impeding water flow.
Increased root growth was observed associated with the clay veins present throughout the substrate. This was attributed to their finer texture resulting in increased moisture and nutrient holding capacity compared to the surrounding substrate.

Influence of root distribution and root function on vine growth

At this site, the amount of vine growth and fruit yield was directly related to root growth. Both M6 and M9 had similar root numbers and root distributions leading to similar above ground growth and similar fruit yield. In contrast, M7 had lower numbers of roots and the lowest vine growth and fruit yield. While vine growth was significantly lower ($P< 0.05$) at profile M7, the average cane weights were 55 – 60 grams per cane indicating that they still had moderate to high vigour (Smart and Robinson, 1991). Vines at both M6 and M9 were considered to have high vigour with average cane weights of 60 – 80 grams per cane. The increased vine growth at these profiles was attributed to a greater supply of moisture (Peterlunger, 2005; Van Leeuwen *et al*, 2006). This was consistent with the estimation of plant available water (PAW), with both M6 and M9 having higher PAW than profile M7. The differences in vine growth were reflected in the image of plant cell density (PCD) with similar higher PCD values were attributed to M6 and M9 profiles compared with the lower values at M7. From the PCD image, it was concluded that the southern aspect had higher vine vigour than the vines on the corresponding northern aspect suggesting that the southern slope had greater access to soil moisture.

The larger root system and greater vine growth at M6 and M9 was complimented with vines at these profiles also having significantly higher yield than those at M7. In both years the higher yield occurred through increased bunch weight. This indicated that vines at profile M7 experienced greater moisture stress than the other profiles which decreased berry size (Ojeda, 2001) and potentially reduced the number of berries per bunch (Kliewer *et al*, 1983; Matthews and Anderson, 1989). Therefore at this site the differences in both vine vigour and fruit yield were attributed to differences in soil moisture supply capacity between the profiles.

The increased soil thickness and moisture holding capacity of both the M6 and M9 profiles allowed the vines to have greater access to nutrients and moisture stored within the soil profile. As discussed in previous chapters, the efficiency of nutrient uptake by roots decreases when the moisture content of the soil is low (Schreiner and Scagel, 2006; Sipiora, 2005). Therefore even though all of the basalt profiles had similar soil chemistry, the availability of these nutrients was lower at M7 as this profile will have increased fluctuations in soil moisture and be more prone to drying, unless irrigation is almost constant through the growing season. The high stone content of the M7 profile also meant there was less soil volume available for root exploration and nutrient uptake than the other profiles (Richards, 1983; Conradie, 2002). The vines at M7 were also more prone to water stress and showed signs of wilting sooner than vines at the other profiles require more irrigation (C. Surios, pers comm.). In contrast, the thicker soil profiles of M6 and M9 had greater capacity to buffer against soil moisture fluctuations. Their position in the landscape, on side slopes and not the crest, also meant that they had increased access to moisture due to subsurface lateral water flow from upslope areas. This occurs through both rainfall and increased irrigation. This increased the resilience of the root systems within these profiles can then enable greater vine growth through increased nutrient uptake. The shallow soil thickness and free draining substrate of the M7 profile and its landscape position also mean there is a greater likelihood of water and nutrient movement away from the site to other down slope parts of the landscape. Therefore water application at M7 has the potential to cause increased growth elsewhere in the vineyard as well as increasing the potential for environmental pollution if over fertilised due to nutrient leaching and through-flow. This is supported by the image of plant cell density (PCD) that demonstrates higher PCD values on the southern slope compared to the northern slope, suggesting these vines have greater access to sub surface laterally flowing moisture and this is supported by seepage being reported at these lower landscape positions (C. Surios, pers comm., Figure 27).

Conclusions

This site shows the influence of soil thickness on vine growth. The increased vine growth and fruit yield was associated with thicker soil depths and larger root systems in absence of other soil limitations. This complements the findings of the Burnt and Unburnt Kurosol profiles discussed in Chapter 3 where the artificially increased topsoil of the Kurosol-Burnt profile enabled greater root growth and subsequently increased above ground growth (vine vigour and yield) as compared to the Kurosol-Scalped profile which had its topsoil artificially thinned. As all the basalt soils had similar high fertility, the difference in root growth was not attributed to variations in soil nutrition. The high root and vine growth at profile M9 demonstrated that the lower levels of exchangeable Ca^{2+} recorded within this profile were non-limiting. Instead, the difference in root growth was attributed to variation in soil moisture supply potential within the profiles that ultimately influenced nutrient uptake. Thicker, less stony soils will allow greater moisture storage and larger volume for roots to explore which lead to the increased vine growth at profiles M6 and M9. They also buffer against moisture deficiencies, even under irrigation management, due to their depth and landscape position. Whereas the thinner and stonier M7 soil profile had reduced access to soil moisture, restricting root growth and reducing both vine growth and fruit yield. The underlying substrate was free draining and had limited capacity to retain moisture, meaning less opportunity for root growth within these substrate layers. Any water not retained by the overlying soil would be able to readily permeate through the landscape and seep to lower slope positions.

Increased root growth was observed within the substrate where zones of higher moisture holding capacity soil occurred, such as clay rich veins.

While all the soil profiles formed were related to the underlying basalt bedrock, they did not develop entirely *in situ* with all upper horizons showing evidence of re-working e.g. truncated clay veins and stone-lines. This has important implications when trying to understand the occurrence of soil types in other parts of the landscape as it shows that many Tasmanian slopes have had active colluviual process. This may mean that the mapped bedrock lithology may not match the typical soil type for that substrate. An examination of root growth and vine performance on differing colluvial soils at this vineyard is discussed in Chapter 7.

6. Vine vigour and yield on dolerite derived soils

Introduction

Dolerite is a key soil parent material throughout central and eastern Tasmania. During the mid-Jurassic (175 – 160 Million years ago) large volumes of basic magma were intruded as dolerite sills as the Australian continent separated from Antarctica. The resulting dolerite now covers approximately 30,000 km^2 of land throughout Tasmania (Seymour *et al*, 2007), or approximately half the land area of island. It forms a resistant layer that dominates the hillcrests and slopes through the central and eastern parts of the State. Much of the soil on the upper and middle slopes of these areas are therefore derived from either dolerite or dolerite derived colluvium.

Certain dolerite derived soils have been targeted for agricultural use due to their mainly free draining nature and relatively high natural fertility. A range of dolerite derived soils are currently utilised for viticulture with vineyards mainly occurring on black cracking clays (Black Vertosols), shallow and stony friable clayey soils (Red and Brown Demosols) and texture-contrast soils with mottled subsoils (Brown Chromosols and Sodosols). Of these, the deeper Brown Demosols appear most suited to viticultural use (Doyle and Farquhar 2000).

The first succinct written summary of soils formed from dolerite in Tasmania was outlined by Nicolls (1958) who described the occurrence of five key soil types: Black soils on dolerite (Bld); Brown soils on dolerite (Bd); Podzolic soils on dolerite (Pd); Krasnozems on dolerite (Kd); and Yellow-brown soils on solifluction deposits from dolerite (Ybs). According to Isbell (1996) these typically classify as Black Vertosols (Bld), Brown or Red Dermosols (Bd), Brown Chromosols or Sodosols (Pd), Red Ferrosols (Kd) and Organosols or Ferrosols (Ybs).

At a detailed mapping scale, Laffan and McIntosh (2005) identified 22 Soil Profile Classes developed from doleritic soil parent materials, highlighting the diversity of soils formed from dolerite. Osok and Doyle (2004) highlighted that many of these soils have a complex stratigraphy and proposed many of the soil horizons relate to different cycles of erosion and deposition as outlined by Bulter (1959). This would help explain the numerous combinations of mapped Soil Profile Classes described by Laffan and McIntosh (2005). It also implies that considerable variation can occur across the landscape within any one soil order.

This chapter describes in detail the physical and chemical characteristics of selected dolerite soils investigated at Frogmore Creek Vineyard. Four soil profiles were selected for detailed analysis and vine measurements, all occurring within one soil order (Vertosols). These sites were chosen based on differences in spectra intensity in infra-red imagery of the vineyard to specifically represented regions of high, medium and low vine vigour. All of the soil profiles were classified as either Black or Grey Vertosols (Isbell, 1996) and had only subtle differences in the Australian Soil Classification (Table 28). Associated vine vigour, vine yield and root distribution were measured at these sites and discussed in relation to soil chemical and physical properties.

Site description

Location

This study site was located at Frogmore Creek Vineyard, situated in the Coal River Valley in south-eastern Tasmania (42° 44’ S, 147° 29’ E), approximately 5 km east of the township of Richmond.

Geology and topography

The lithology of the main ridge in the local area has been mapped as Jurassic dolerite overlying a bedrock of medium-coarse sandstone with minor mudstone of Triassic age (Leaman, 1975). A small section of doleritic colluvium was mapped by Leaman (1975) on the upper part of the mid slope but present field observations demonstrate this extends much further down slope (Figure 36). The studied vine block was located across the mid and lower slope dominated by a dolerite ridge to the west. A Jurassic dolerite ridge caps the underlying Triassic sedimentary layers of sandstone and some minor mudstone (Figure 36). These Triassic sediments were evident close-by to the vineyard with sandstone outcropping at the mid-slope of the adjacent slope.

Existing Soil Maps

The full extent of the vineyard has previously been mapped across two 1:100,000 scale Reconnaissance Soil Map sheets (Figure 37), with the southern portion of the vineyard covered by the Hobart map sheet (Spandswick and Kidd (2000a) and the northern section included on the Brighton map sheet (Spandswick and Kidd (2000b). These indicate the soils on the upper slopes as Brown soils on dolerite (Bd1), with the lower slopes mapped as Podzols and Podzolic soils on sandstone (Pss). The area has also been mapped at a detailed 1:5,500 scale by Chilvers (1998), who produced soil map of the site prior to vineyard establishment. In his survey, Chilvers (1998) mapped the upper slopes as Black soils on dolerite, with the lower slopes mapped as Black dolerite colluvium over mudstone.

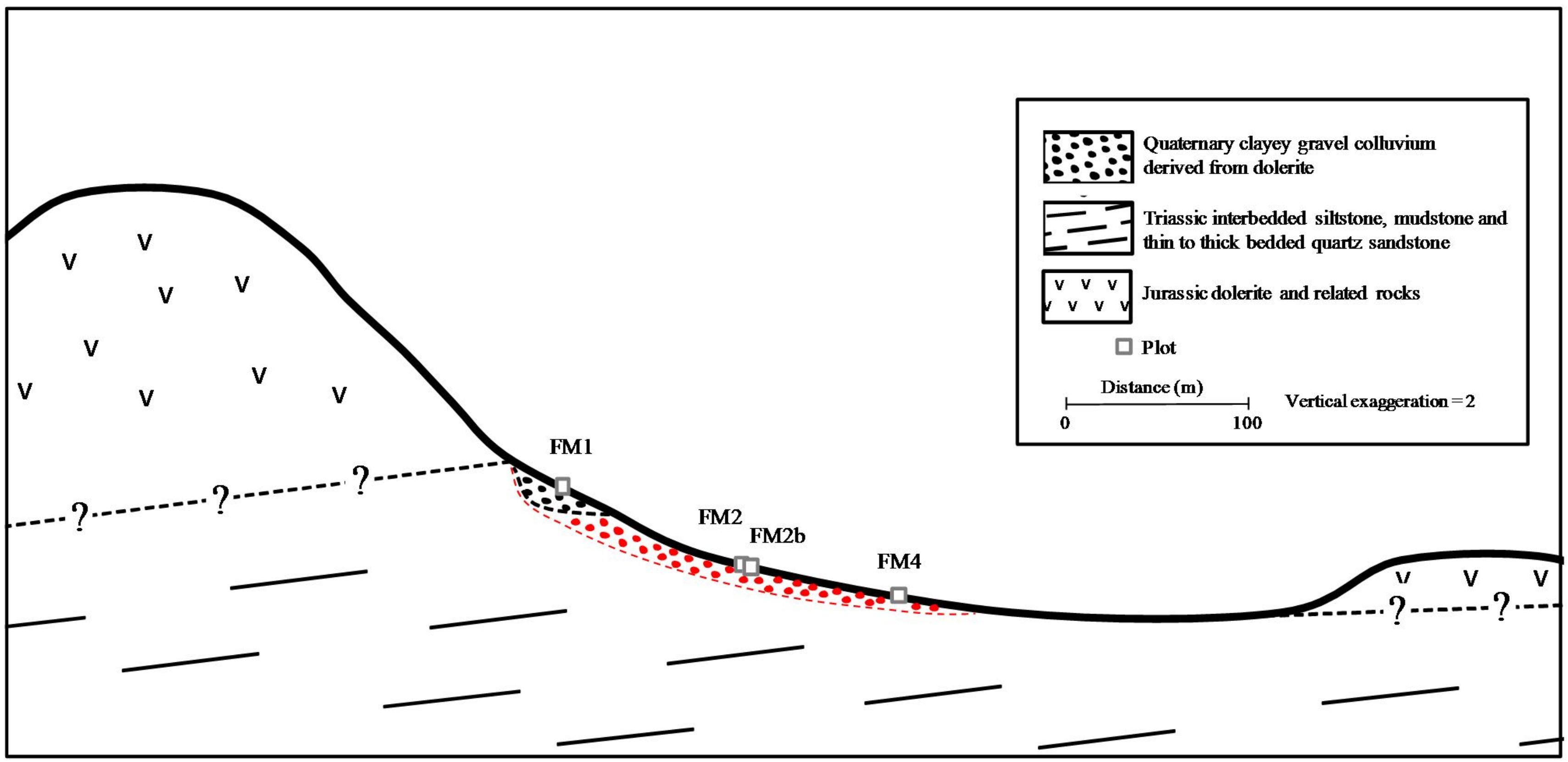

Figure 36: Cross-section of the study site derived from 1:25 000 scale geology map. The field distribution of soil derived from dolerite (shown in red) occurred over greater proportion of the slope than inferred by the geology map.

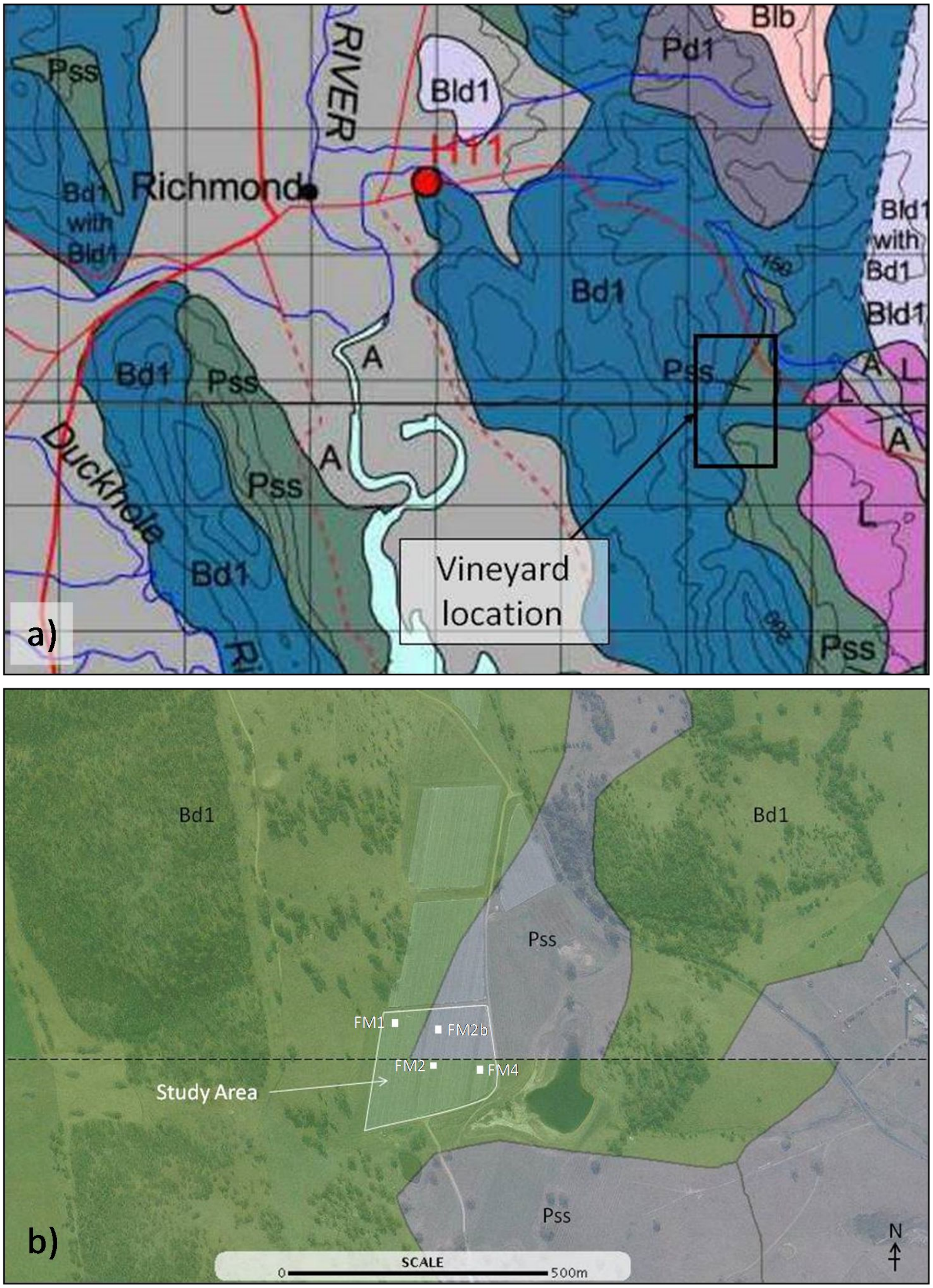

Figure 37: Existing soil information of the study site. The studied block crossed the boundary between the Brighton (north) and Hobart (south) Soil Maps, indicated by the black dashed line. Soil types described are: Bd1 – Brown soils on dolerite; Pss – Podzol and Podzolic soils on sandstone. a) 1:100,000 scale soil map. b) soil overlay on an aerial photograph showing the vineyard block studied.

Individual site layout

The studied area of the vineyard was established in 1998 with own-rooted *Vitis Vinifera* cv Pinot Noir (G5V15) with a row and vine spacing of 3 m and 1.4 m respectively. Rows were aligned across the slope, in a north-south orientation. Vines were pruned to 40 buds on a VSP trellis. The vineyard was established and managed organically until 2008 when herbicides were introduced to control the large number of weeds present. All vines were within the one vineyard block and had similar management practices applied. Plots were confined within one block to prevent any differences in vine variety, clone and trellising system.

Overhead irrigation was installed as a frost protection measure and was initially also used to irrigate the vines during establishment. The overhead irrigation was located on every fifth row. The irrigation system has since been upgraded with the vineyard now irrigated using a dripper line located in every row. Inter-rows were alternatively cultivated and re-sown each year (mainly clover and ryegrass) resulting in rejuvenation of the inter-row every second year.

Plot layout was consistent with those outlined in the chapter “General Methods”. Plots were established with a one row buffer from the overhead irrigation as shown in Figure 38. The soil trench was excavated in the central uncultivated row.

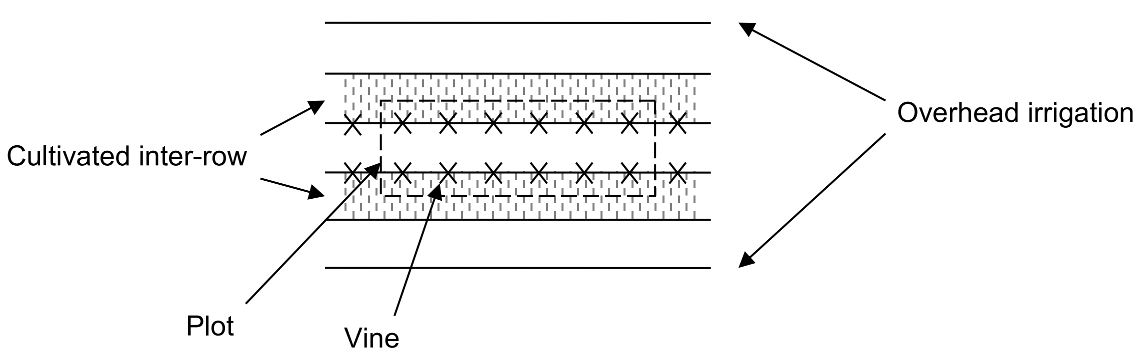

Figure 38: Schematic diagram of plot layout.

Climate background at site

The closest weather station with records greater than 10 years was Hobart Airport (station 094008), situated 10 km to the south of the study area. Summaries of mean maximum temperature and rainfall recorded at this site are shown in Chapter 5.

The Mean Annual rainfall for the region was 500 mm/yr with slight winter dominance although distribution is relatively consistent throughout the year. Both the 2006-07 and 2007-08 seasons had below average rainfall although rainfall during the summer months (Dec – Feb) was generally higher than normal. The 2005-06 season had average annual rainfall however this dominantly occurred during winter, with the remaining months receiving below average rainfall. Mean monthly maximum temperature ranges from 22.5^{o}C in January to 12.4 in July. During ripening the mean temperature cools from a mean of 22.4^{o}C (February) to 18.1^{o}C (April) while rainfall increases slightly from a monthly mean of 36.6 mm to 43.2 mm, respectively. The average monthly temperature was slightly above the long-term average in all years.

Results

Remote sensing

Infra-red analysis of plant cell density was flown by SpecTerra Services in February 2006. The images of plant cell density (PCD) of the study area are shown in Figure 39. The left hand image shows a smoothed PCD surface of the detailed data (shown in right hand image). Blue colours indicated areas of high PCD (and therefore indicate higher vigour) and grade to red colours indicating low PCD (low vigour). These differences in vigour were used to locate the studied plots. FM2 and FM2b were located within the highest vigour, FM1 was located within moderate vigour and FM4 within an area of lowest vigour. The horizontal banding of the images corresponds to regular rows of low vigour, with the detailed image clearly shows these rows as red bands across the block. This striking difference in vine growth corresponds to the rows where the overhead irrigation was located. It is assumed that the use of this irrigation system caused excess grass competition along these rows during the first few years of vineyard establishment. Young vines are particularly susceptible to weed competition (Due *et al*, 1999) and so their early growth was restricted. This competition has since been removed however these vines have always remained less vigorous than the surrounding rows (Tony Scherer, pers. comm.). Each plot was therefore buffered from the overhead irrigated rows to minimise the impact of this vigour difference (Figure 38).

The electromagnetic (EM) survey is shown in Figure 40. The horizontal dipole image (left-hand image) shows a high response in the upper portion of the block. The clear boundary separating this area corresponds to a break in slope. The vertical dipole (right-hand image) shows a response over a larger area in the upper slope, and has a stronger response in the bottom portion of the block (around FM4).
An edge effect can be observed in both dipole orientations. It is assumed that this was mainly due to the lack of trellis (and hence no influence from wire or metal posts), but could also be due to lower soil moisture values as the area outside the block was not irrigated.

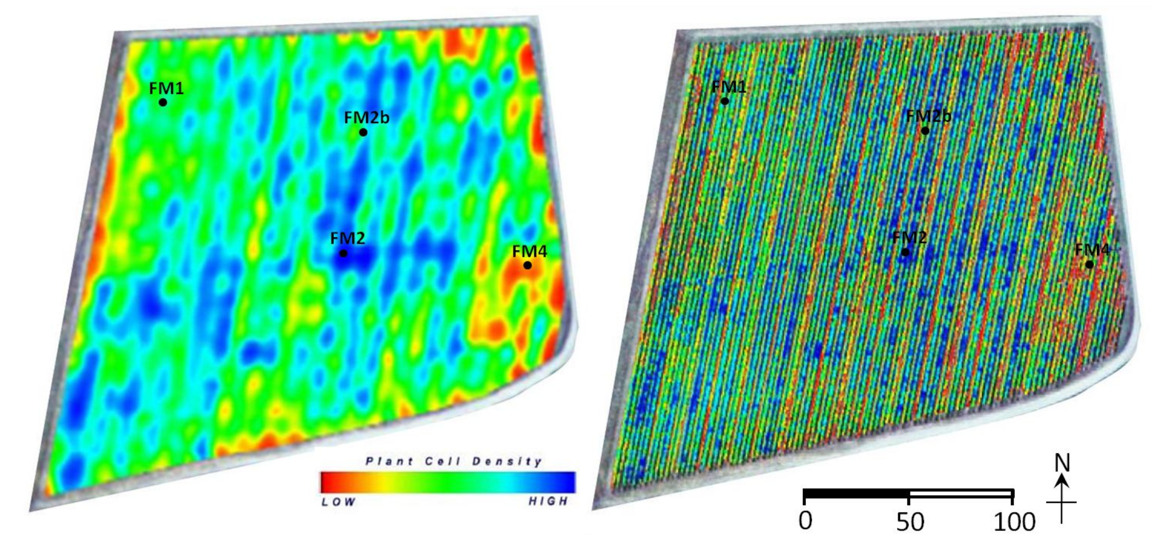

Figure 39. Infra red image of plant cell density (vine vigour). The left image is a smoothed surface of the individual vine data (right). The vertical banding corresponds to rows with overhead irrigation. This is clearly shown as red lines on the detailed image. Plot locations are marked across each vigour zone.

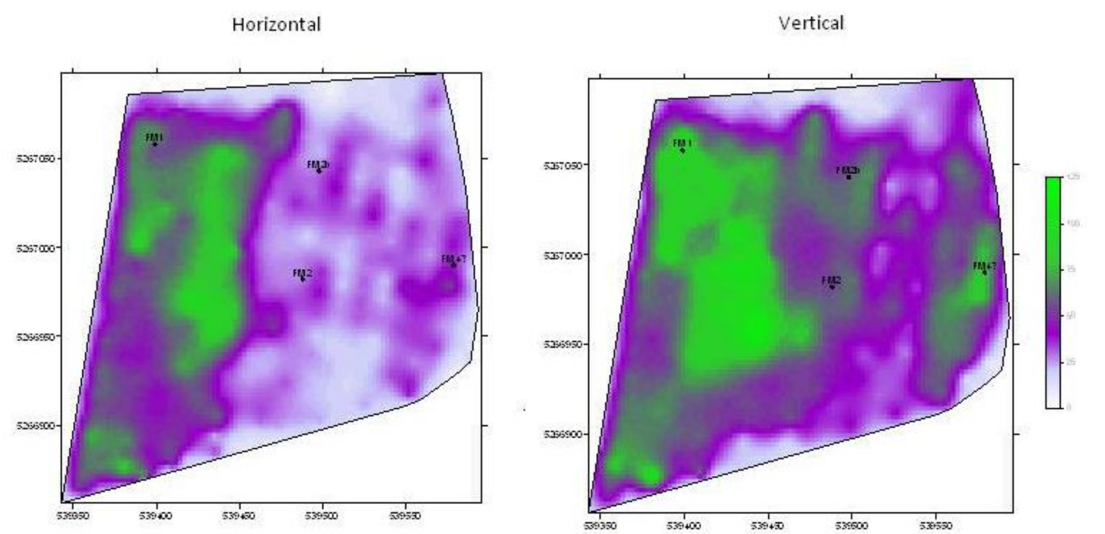

Figure 40: Electromagnetic survey of the study area. Green shows areas of higher conductance while purple grading to white shows lowering conductance. Location of plots are marked

Summary soil descriptions

Profile FM1 was located on the upper slope of the study area, beneath a steeper doleritic back-slope. This was the deepest profile examined (> 1.5 m) and consisted of a thick black clay loam topsoil overlying brown clayey subsoils. According to the Australian Soil Classification (Isbell, 1996) it classified as an Endocalcareous, Self-mulching, Black Vertosol. Many cracks were evident throughout the profile extending down to below 80 cm. This was predominantly through a moderately developed, prismatic primary structure that had developed across the horizons. Towards the top of the prisms this primary structure parted to either weakly developed angular blocky or weakly developed polyhedral secondary structure. At depth (> 60 cm) the prisms parted to moderately developed lenticular structure, indicating the reactive and moist nature of the clay in these horizons. This was supported by slickensides being present on the ped faces. The surface soil had a strongly developed self-mulching structure, allowing it to in-fill cracks that opened to the surface. Topsoil-lined cracks were repeatedly observed throughout the profile. Soft carbonate was visible in the lower subsoil (> 60 cm) (Figure 41) and had a strong reaction to HCl indicating that the lower horizons of the profile were calcareous.

Figure 41: Profile FM1. Note the free carbonate at depth. Large roots can be seen growing through cracks of upper subsoil horizons.

Profiles FM2 and FM2b were situated in the middle of the block where the slope angle reduced and the site became flatter. Both these profiles were situated within the same vineyard row however FM2b was located on a slight rise and therefore slightly elevated when compared to FM2.

FM2 and FM2b were moderately deep (< 80 cm) gradational profiles (Northcote, 1979) with a moderately thick black clay loam topsoil overlying olive brown clayey subsoils. Weathered Triassic sandstone bedrock was present below 75 cm. Both profiles classified as a Haplic, Self-mulching, Black Vertosols (Isbell, 1996). Accumulation of carbonate was visible in both the lower subsoil horizons and throughout the underlying rock in both profiles (Figure 42 and Figure 43). Moderate to strongly developed coarse columnar structure dominated the subsurface horizons with cracks extending to the underlying sandstone. As the soil dries these cracks widen considerably allowing the self-mulching topsoil to fall in. Dark coloured topsoil-lined cracks were regularly observed at depths at 60 cm and below (Figure 44).

Figure 42: Soil Profile FM2. Note the strongly developed columns that become more visible as the soil dries. The columns continued to the underlying weathered sandstone (80 cm), where white calcium carbonate deposits can be seen at their base.

Figure 43: Soil Profile FM2b. Cracks of the coarse columnar structure extend to the underlying bedrock (sandstone). The brown lower soil horizon above the sandstone is a truncated remnant of an older soil that has later been buried by more recent dolerite colluvium.

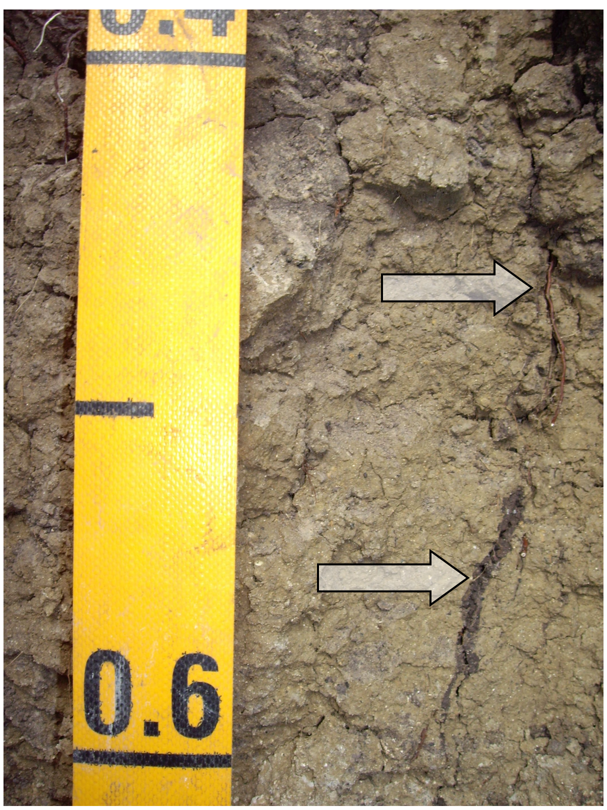

Figure 44: Topsoil-lined crack to a depth of 60 cm (arrowed). A root can be seen following the same pathway at 40 – 50 cm (upper arrow). This highlights the inVERTing process common to all VERTosols *(photo taken at FM2)*

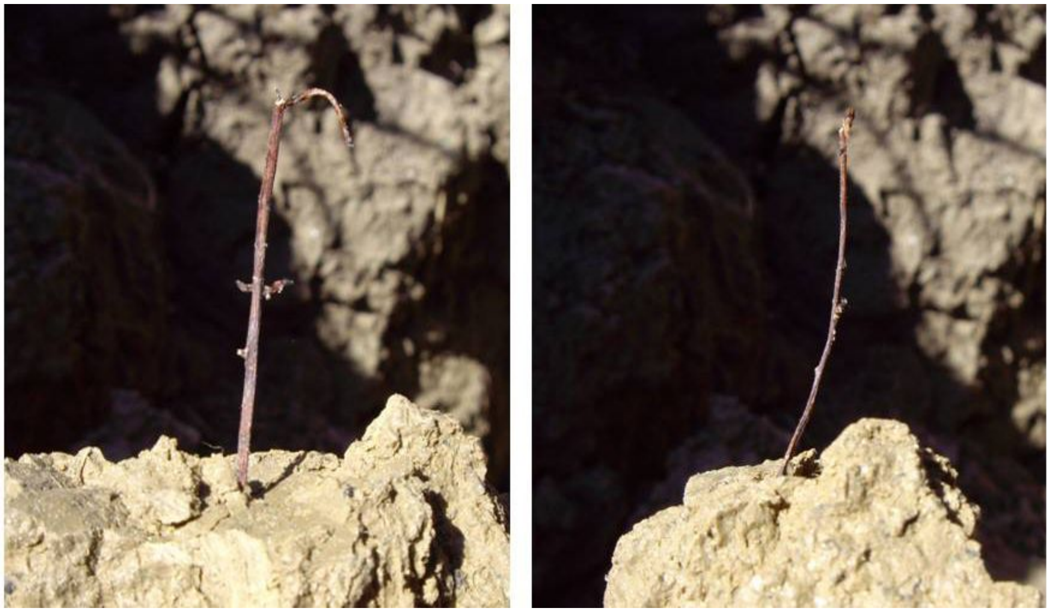

Figure 45: Flattened root growth due to expanding clay structure. The two images are of the same root turned through 90 degrees and demonstrate the root has been flattened with one dimension wider than the other *(profile FM4).*

Profile FM4 was located on the lower footslope and thus situated at the lowest slope position in the study area. It was the shallowest profile observed, with the dolerite derived colluvium overlying fine sandstone and mudstone bedrock at 70 cm. A stone-line of rounded calcrete gravels and cobbles was present at the boundary between soil and substrate; however a further clayey horizon was occasionally present below this stone-line and above the bedrock. This highlights the irregular erosion that occurred across the sandstone landscape prior to being overlain with younger doleritic colluvium. Some calcium carbonate accumulation was present within the weathered sandstone suggesting leaching of calcium from the mafic doleritic colluvium into the siliceous substrate. This profile was classified as a Haplic, Epipedal, Grey Vertosol (Isbell, 2002).

Figure 46: Soil profile FM4. Solum colour was dominantly grey, particularly in the subsoil horizons. Rounded calcrete coarse fragments are visible throughout the lower subsoil and form a stone-line above the weathered Triassic sandstone.

The observed soil profiles all had moderately or strongly developed coarse primary structure that extended across horizons. These were mainly described as prisms throughout the lower horizons with only the upper most horizon described as a columns if a rounded top was present. The classification of these profiles was therefore also very similar (Table 28). The greatest difference occurred at FM4 which differed at both the Great Group and Suborder level. This was due to the dominance of grey colours in the subsoil and the lack of a self-mulching topsoil. FM1 was slightly different in classification to FM2 and FM2b at the Subgroup level. This was due to the abundance of free calcium carbonate within the subsoil of this profile.

Table 28: Soil classification summary of profiles at Frogmore Creek Vineyard

Soil Profile	Order	Suborder	Great Group	Subgroup	Family criteria				Slope angle (%)	Drainage Class
					Gravel (surface and A1)	Upper clay content (< 0.1 m)*	Max clay content of B horizon*	Soil depth		
FM1	VE	AE	EI	FZ	E	Q	R	X	15	M-W
FM2	VE	AE	EI	CD	F	Q	R	V	8	M-I
FM2b	VE	AE	EI	CD	F	Q	Q	V	7	M-I
FM4	VE	AD	GS	CD	E	Q	Q	V	5	I

*estimated from field texture

Key to Classification codes:

FZ – Endocalcareous

CD – Haplic

EI – Self-mulching

GS – Epipedal

AE – Black

AD – Grey

VE – Vertosol

E - Non-gravelly (< 2 %)

F - Slightly gravelly (2 – 10 %)

Q – Fine (clay content < 45 %)

R – Medium fine (clay content 45 %)

X – Very deep (1.5 – 2 m)

V – Moderately deep (0.5 - < 1.0 m)

M-W – Moderately well drained

M-I – Moderate to imperfectly drained

I – Imperfectly drained

Table 29: Summary of key profile features at Frogmore Creek Vineyard.

Horizon	Depth (cm)	Colour (moist)			Texture	Structure Primary				Secondary			Consistence
FM1													
A11p	0 – 8	10YR	2	1	LC	S	m/f	GR					Firm
A12	8 - 22	10YR	2	1	LC	M	m-c/c	PR	=>	Wk	m	PO	Firm
B21	22 - 57	2.5Y	3	1	LMC	M	m-c/c	PR	=>	Wk	m	AB	Firm
B22	57 - 79	10YR	3	3	LMC	M	m-c	PR	=>	M	m-c	LE	Firm
B23	79-128+	10YR	3	4	LMC	M	m-c	PR	=>	M	m-c	LE	Firm
FM2													
A11p	0 - 4	2.5Y	2.5	1	SCL	M	f	PO	+	M	M	AB	Firm
A12	4 - 11	2.5Y	2.5	1	CL	M	m-c	AB	=>	W	m	AB	Weak
B21	11 - 33	10YR	3	2	LC	S	c-vc	CO	=>	M	m-c	PR	Firm
2B22	33 - 53	2.5Y	4	4	LMC	M	c-vc	PR	=>	M	m-c	AB	Firm - strong
2B23	53 - 74	2.5Y	4	4	LMC	M	c-vc	PR	=>	M	m-c	AB	Firm - strong
C	74-125+				fSL								Strong-v.strong
FM2b													
A1p	0 – 10	10YR	2	1	gCL	S	f	PO	+	S	m	PO	Weak-Firm
B21	10 - 26	10YR	2	1	LC-	S	c-vc	AB	=>	M	m-c	AB	Firm
2B22g	26 - 45	2.5Y	3	2	LC	S	c-vc	PR	=>	M	m-c	AB	Firm
2B23g	45 - 78	2.5Y	4	4	LC-	M	c-vc	PR	=>	M	m-c	AB	Firm
3B24	78 - 90	10YR	4	6	LC-	M	m-c/c	AB					Firm
C	90-136+				fSL								Strong-v.strong
FM4													
A11p	0 – 5	10YR	2	1	CL	M	f	PO	+	M	Vf	GR	Firm
A12	5 - 11	10YR	2	1	LC	M	m-c	AB					Firm
B21	11 - 31	2.5Y	4	2	LMC	S	c-vc	CO	=>	M	m-c	AB	Firm
2B22	31 - 47	2.5Y	4	3	LMC	S	c-vc	PR	=>	M	m-c	AB	Firm
3B23	47 - 67	2.5Y	4	4	LC	M	m-c	LE					Firm
4B24	67 - 83	2.5Y	4	3	LC	M	m-c	LE					Firm
C	83 – 90+				fSL								Strong-v.strong

See Appendix 1 for a description of codes

Soil chemical analysis

The soil chemical signatures of the soil profiles were very similar and demonstrate hat these soils are closely related (Figure 47 & Table 30).

Each profile had an alkaline reaction trend with depth, with slightly acidic surface horizons increasing to alkaline values ($pH_w > 8$, $pH_{CaCl_2} > 7.5$) in horizons below 60 cm. This was associated with an accumulation of calcium carbonate in these lower horizons and high base cation status throughout. Electrical conductivity ($EC_{1:5}$) also increased with depth and was generally low in the topsoil (< 0.2 dS/m) and increased to moderate values in the subsoil (0.6 - 0.8 dS/m). Organic carbon was high (> 4 %) in the surface horizons (< 40 cm) and had a decreasing trend with depth. Effective cation exchange capacity (ECEC) was also high throughout the profiles and was dominated by exchangeable $Ca^{2+}$and Mg^{2+}. The high Ca^{2+} values in the surface horizons were most likely due to the application of lime during vineyard establishment (Scherer, pers comm.). This would also explain the slightly higher pH observed in the upper most horizon of each profile. FM2b showed an accumulation of exchangeable Ca^{2+} and Mg^{2+} at depth, associated with a stratigraphically different subsoil horizon (3B24).

The topsoil values of exchangeable K^+ were generally high (>0.5 cmol(+)/kg) and decreased with depth to between 0.2-0.3 cmol(+)/kg. Exchangeable K^+ accumulated with depth in both FM1 and FM4, suggesting some leaching of the upper portion of the profiles. The high values of exchangeable K^+ within the topsoils may be in part due to fertiliser application. Exchangeable Na^+ generally followed a similar trend with highest values occurring in subsoil horizons. However all profiles except for FM1 have a decline in exchangeable Na^+ within lower subsoil horizons. The exchangeable sodium percentage (ESP) showed that all profiles also had horizons classed as sodic (ESP > 6%). Both FM1 and FM4 increased in sodicity with depth and had lower horizons with an ESP of 9-10 %. The ESP trend of FM2 and FM2b were slightly different however, with highest values within the mid-subsoil (approx 30 - 60 cm). No dispersion (Emmerson, 1969) was observed for any soil horizon, even for those classed as sodic (based on ESP of > 6 %).

Analysis of linear shrinkage showed that all profiles had highly reactive clays present. FM1 had the most reactive profile, with almost all horizons having shrinkage greater than 20 %. The topsoil at FM4 had the lowest shrinkage values (11.9 %) and this may in part be due to the absence of self-mulching properties.

Soil Penetration Resistance

Penetration resistance values generally increased down the soil profiles (Figure 48). Topsoil values were consistent between the profiles and were generally low (< 1 MPa). Penetration resistance values within the subsoil were generally higher at FM1 compared to both FM2b and FM4, with an average resistance value of 2.1 MPa compared with1.6 MPa and 1.5 MPa respectively. However, both FM2b and FM4 had localised high penetration resistance values (> 3 MPa) at the base of the profiles, highlighting the weathered underlying bedrock. Zones of calcium carbonate accumulation in the upper part of the bedrock had lower penetration resistance values (between 1.5 – 2 MPa). Localised changes in resistance values occurred in all profiles. The variation reflects the coarse primary structure of the profiles, with resistance values through the subsoil (20 – 80 cm) reflecting the coarse columnar soil structure. Zones of lower penetration resistance occurred close to cracks and between structural units, generally decreasing by 0.5 – 1 MPa. Higher values of penetration resistance were measured within the centre of the columns.

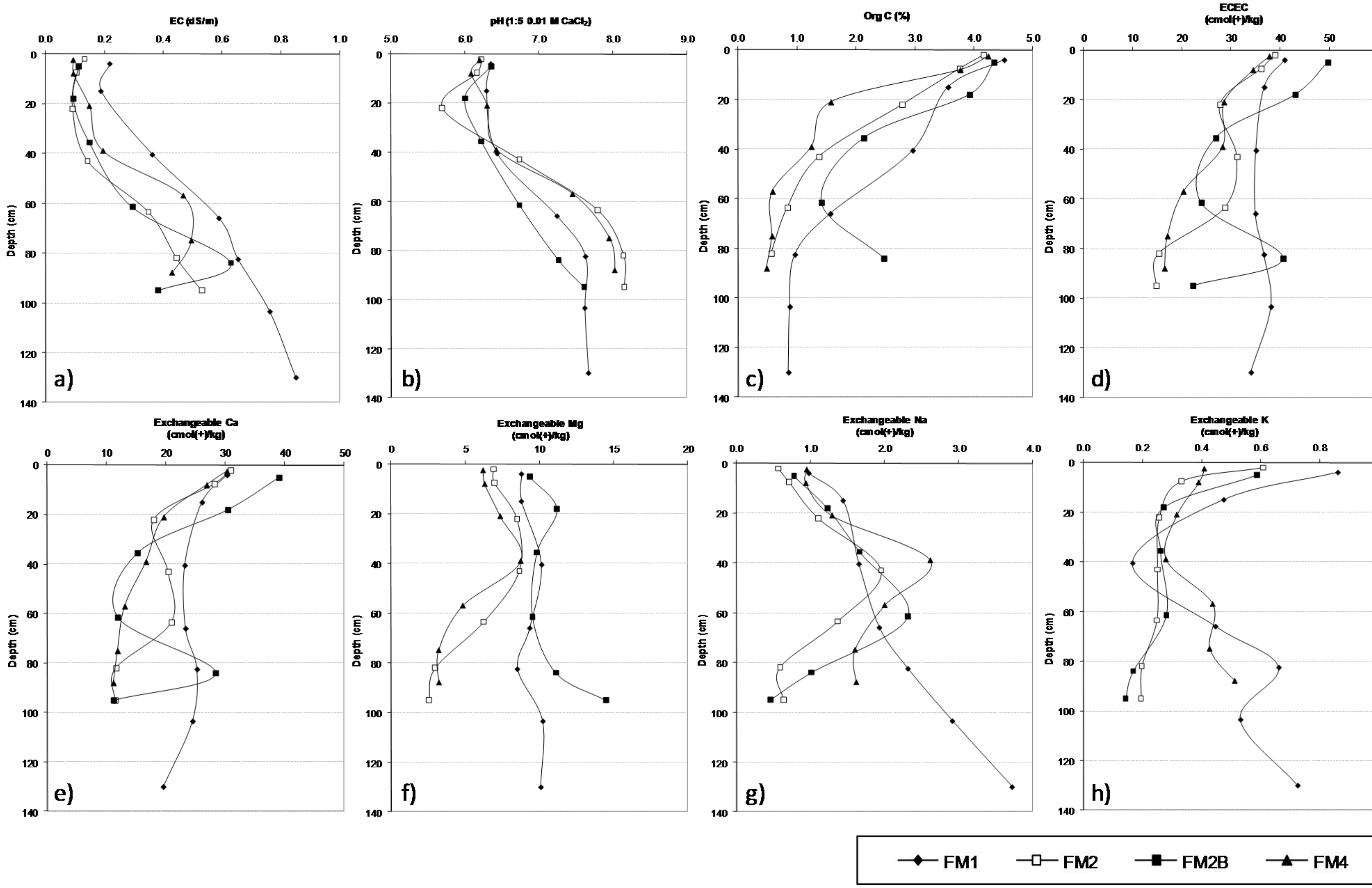

Figure 47: Combined soil chemistry of the profiles at Frogmore Creek Vineyard showing all profiles have the same general chemical depth trends.

Table 30: Analysed soil chemistry.

Horizon	Depth (cm)	pH (1:5) H_2O	pH (1:5) $CaCl_2$	EC (dS/m)	Exchangeable Cations (cmol(+)/kg) Ca^{2+}	Mg^{2+}	Na^+	K^+	ECEC	ESP (%)	Org C (%)	Linear Shrinkage
FM1												
A11p	0-8	6.8	6.4	0.22	30.3	8.8	1.0	0.9	40.9	2.4	4.5	18.2
A12	8-22	6.7	6.3	0.19	26.0	8.8	1.4	0.5	36.8	3.9	3.6	21.0
B21	22-59	7.0	6.4	0.36	23.1	10.1	1.7	0.2	35.1	4.7	3.0	22.1
B22	59-73	8.1	7.2	0.59	23.3	9.4	1.9	0.4	35.0	5.5	1.6	24.0
B23	73-92	8.3	7.6	0.66	25.2	8.5	2.3	0.7	36.7	6.3	1.0	22.3
B24(1)	92-115	8.2	7.6	0.76	24.5	10.2	2.9	0.5	38.1	7.6	0.9	23.0
B24(2)	115-145+	8.3	7.7	0.85	19.5	10.1	3.7	0.7	34.1	10.9	-	23.7
FM2												
A11p	0-4	6.2	6.2	0.13	30.9	6.9	0.6	0.6	39.0	1.4	4.2	13.6
A12	4-11	6.3	6.2	0.10	28.1	7.0	0.7	0.3	36.1	2.0	3.8	13.7
B21	11-33	5.8	5.7	0.09	17.9	8.5	1.1	0.3	27.8	4.0	2.8	14.6
2B22	33-53	7.1	6.7	0.14	20.4	8.7	1.8	0.3	31.2	5.8	1.4	15.0
2B23	53-74	8.3	7.8	0.35	20.9	6.3	1.4	0.3	28.8	4.7	0.8	17.8
C1	74-90	8.6	8.1	0.45	11.6	3.0	0.6	0.2	15.3	3.8	0.6	-
C2	90-125+	8.5	8.3	0.74	17.5	6.6	1.6	0.2	26.1	6.1	-	-
FM2b												
Ap	0-10	6.1	6.4	0.11	39.0	9.4	0.8	0.6	49.7	1.6	4.3	17.7
B21	10-26	5.8	6.0	0.09	30.4	11.2	1.2	0.3	43.1	2.9	3.9	19.9
2B22g	26-45	6.0	6.2	0.15	15.2	9.8	1.7	0.3	26.9	6.2	2.1	20.8
2B23g	45-78	6.9	6.7	0.30	11.8	9.6	2.3	0.3	24.0	9.6	1.4	21.7
3B24	78-90	7.5	7.3	0.63	28.3	11.1	1.0	0.2	40.6	2.5	2.5	20.0
C	90-100	7.8	7.6	0.38	11.2	10.5	0.5	0.1	22.2	2.1	-	-
FM4												
Ap	0-5	6.2	6.2	0.10	30.2	6.2	0.9	0.4	37.8	2.5	4.2	11.9
A1	5-11	6.1	6.1	0.10	26.8	6.3	0.9	0.4	34.5	2.7	3.8	12.6
B21	11-31	6.4	6.3	0.15	19.6	7.4	1.3	0.3	28.6	4.5	1.6	18.6
2B22	31-47	6.7	6.4	0.20	16.6	8.8	2.6	0.3	28.3	9.3	1.2	19.8
2B23	47-67	7.8	7.5	0.47	13.3	4.8	2.0	0.4	20.3	9.9	0.6	17.2
C1	70-79	8.2	8.0	0.50	11.8	3.2	1.6	0.4	17.1	9.4	0.6	-
C2	80-96	8.4	8.0	0.43	11.1	3.2	1.6	0.5	16.5	9.8	-	-

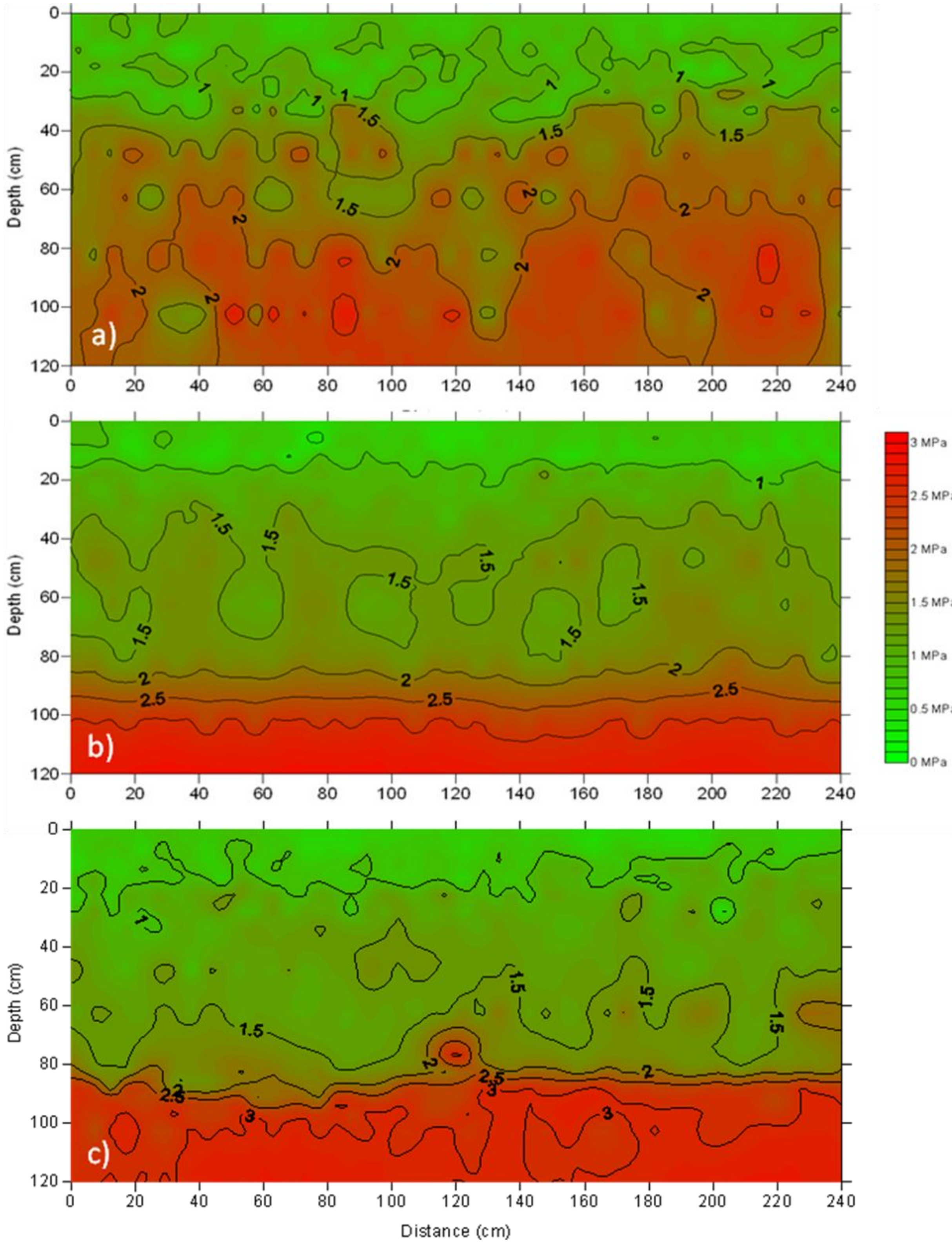

Figure 48: Soil penetration resistance at Frogmore Creek Vineyard. Soil profiles are a) FM1; b)FM2b; and c) FM4. Bands of lower resistance values can be seen within the subsoil and reflect cracks and areas of topsoil in-fill.

Root distribution

The root distribution observed within the soil profiles is shown in Figures 49 to 51. The fine root (< 1 mm) abundance peaked at 10 – 30 cm in most profiles. However, fine roots were also observed to grow and spread throughout the entire subsoil, with some areas of concentrated root growth (or hotspots) occurring at depth normally associated with the base of structural cracks. Fine roots (< 1mm) were the dominant size class across all of the soil profiles and made up 80 – 90 percent of the total root number (Table 31). This relates to 5 – 10 times more abundant than the next size class (1 – 2 mm) and approximately 40 times greater than the 2 – 5 mm size class. Large roots (> 5mm) were only observed in low numbers and no roots of this size class were observed at FM4.

Within FM1, the fine roots were the dominant roots size class and made up over 90 % of all root observations at this profile. The next dominant root class were those 1 – 2 mm in diameter (7.6 % of observations). These were spaced relatively evenly throughout the profile (Figure 49b) and occurred mainly associated with cracks. The remaining root classes (2 – 5 mm and > 5 mm) were only sparsely observed and together they only accounted for 2.2 % of the root observations across the profile face. The 2 - 5 mm root class was the most widely distributed (Figure 49c) and more abundant than the > 5 mm roots (1.6 % of observations compared with 0.6 % for > 5 mm roots). The > 5 mm roots were quite localised, only occurring on one half of the profile face and mainly found within the top 40 cm (Figure 17d). Most of the larger root sizes were observed within cracks.

The dominant root growth at FM2b was also of fine roots (< 1 mm), accounting for 87.2 % of the total root observations. These were mainly concentrated in the upper horizons (< 40 cm) however they were also observed at dispersed locations throughout the entire profile (Figure 50a). The 1 - 2 mm roots followed a similar distribution pattern and were found throughout the entire profile with a slight concentration in the upper soil layers (Figure 50b). However the proportion of root observations of this size class was less, at only 10.2 % of the total root observations. The remaining 2.5 % of observations were due to the larger root classes (2 - 5 mm and > 5mm). Only limited observations of these root classes were recorded and these were mainly in the upper portion of the profile (< 60 cm) (Figures 50c & 50d).

FM1 had the highest total root number (1906 total roots) with total root number tending to reduce down the slope (FM2b – 1659, FM4 – 1539, see Table 31). This was mainly caused by lower numbers of fine roots for both FM2b and FM4 (1446 and 1278 respectively) when compared to FM1 (1720). Numbers of large roots (> 5 mm) also followed this trend albeit in much lower numbers (12, 8 and 0 for FM1, FM2b and FM4 respectively). However, the abundance of mid-sized roots (1 – 2 mm) went against this trend with highest numbers observed at FM4 (228) and lowest numbers at FM1 (144). FM1 had highest numbers in all root classes at depth (> 65 cm) except for the largest root class (> 5 mm) of which there were no observations at any profile below this depth.

Root observation at FM4 showed a distinct vertical banding of the distribution (Figure 51). This was very clear in the distribution patterns of the fine (< 1 mm) and medium (1 - 2 mm) roots. These concentrations of roots reflected the primary soil structure and demonstrate most roots were growing associated with cracks (Figure 52). Nearly all roots were contained within the solum, with only a few isolated fine roots observed within very weathered areas of substrate. No large roots (> 5 mm) were observed at this site.

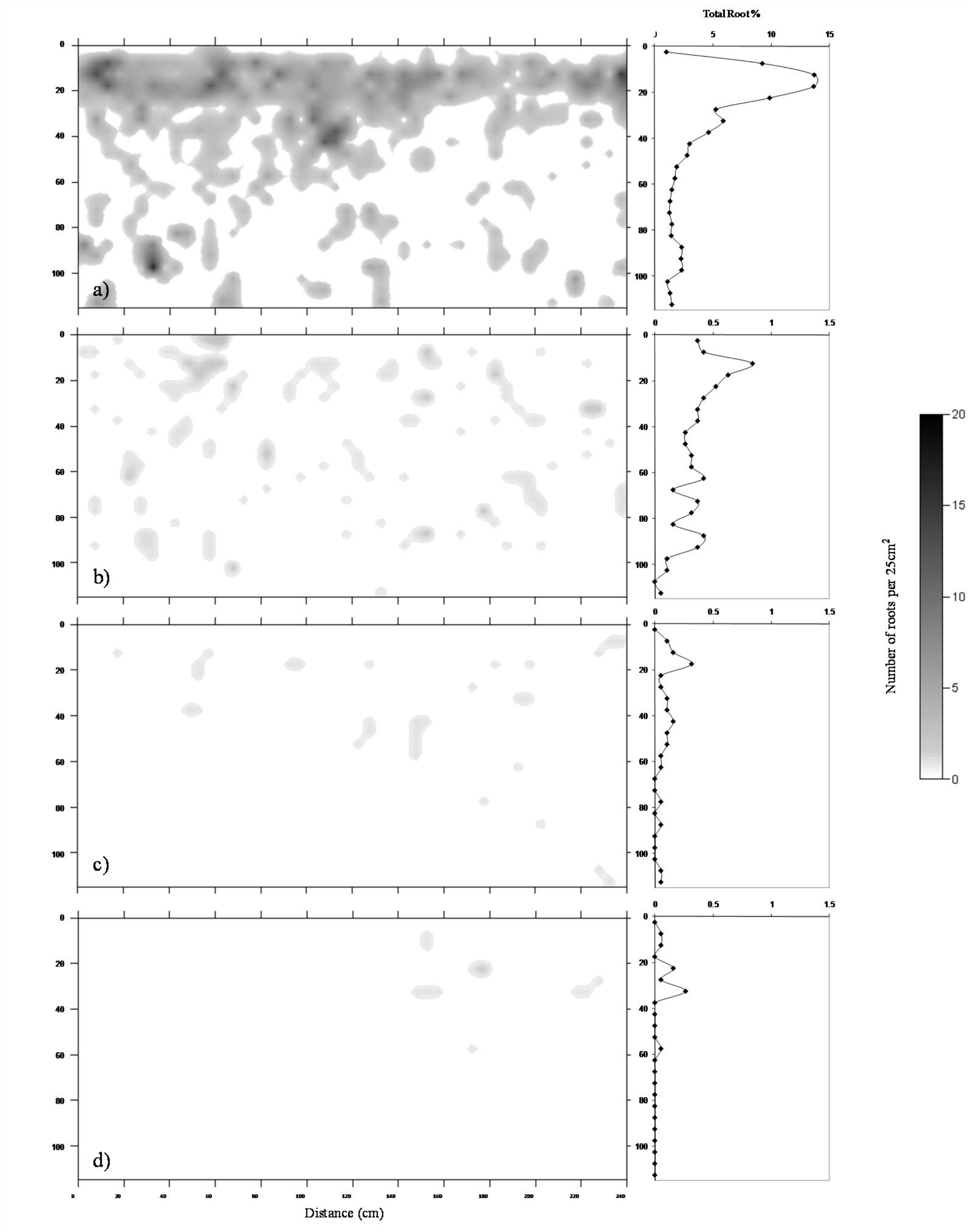

Figure 49: Root distribution of profile FM1 showing the distribution of the following diameter classes: a) < 1mm; b) 1 – 2 mm; c) 2 – 5 mm; d) > 5 mm. Darker shading indicates higher root density. The right-hand graph shows the percentage of total roots for each size class with depth. Note: the scale for < 1 mm root class is ten times greater than the other classes demonstrating the abundance of this root size class.

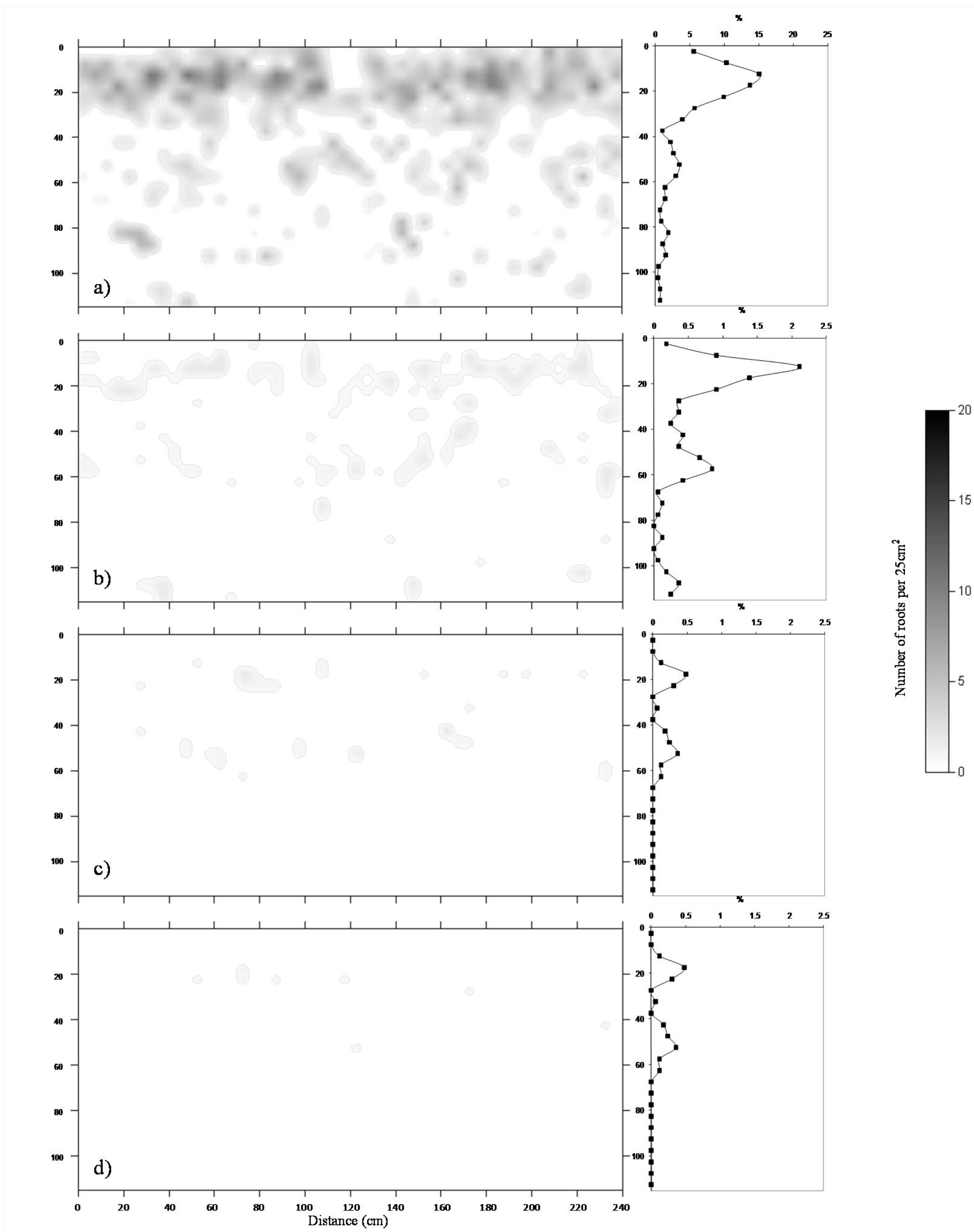

Figure 50: Root distribution of profile FM2b showing the distribution of the following diameter classes: a) < 1mm; b) 1 – 2 mm; c) 2 – 5 mm; d) > 5 mm. Darker shading indicates higher root density. The right-hand graph shows the percentage of total roots for each size class with depth. Note: the scale for < 1 mm root class is ten times greater than the other classes

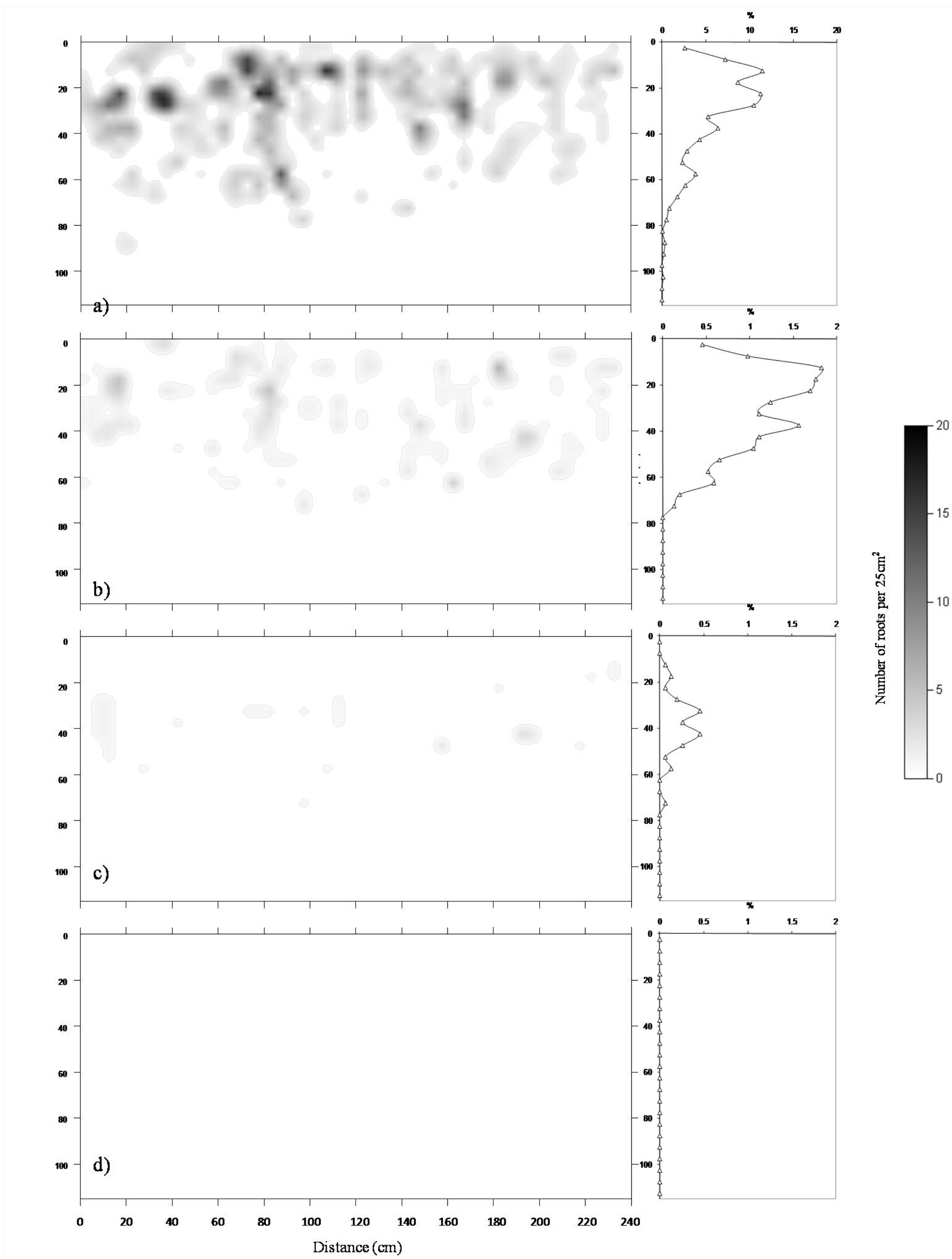

Figure 51: Root distribution of profile FM4 showing the distribution of the following diameter classes: a) < 1mm; b) 1 – 2 mm; c) 2 – 5 mm; d) > 5 mm. Darker shading indicates higher root density. The right-hand graph shows the percentage of total roots for each size class with depth. Note: the scale for < 1 mm root class is ten times greater than the other classes. No roots > 5 mm were observed within this profile.

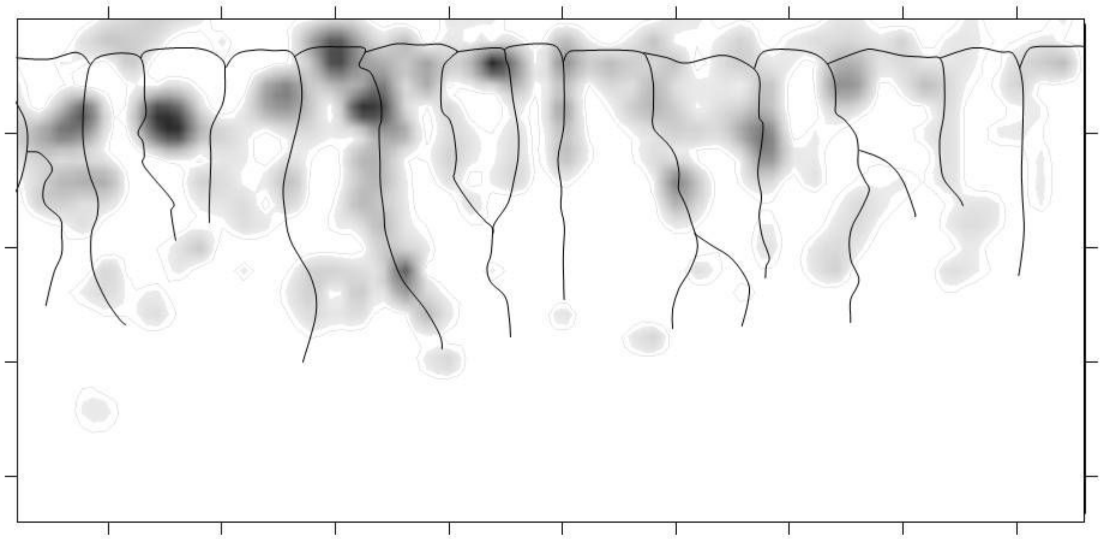

Figure 52: FM4 coarse soil structure, as delineated by cracking pattern, laid over the fine root (< 1 mm) distribution.

Root numbers with depth for the different root size classes

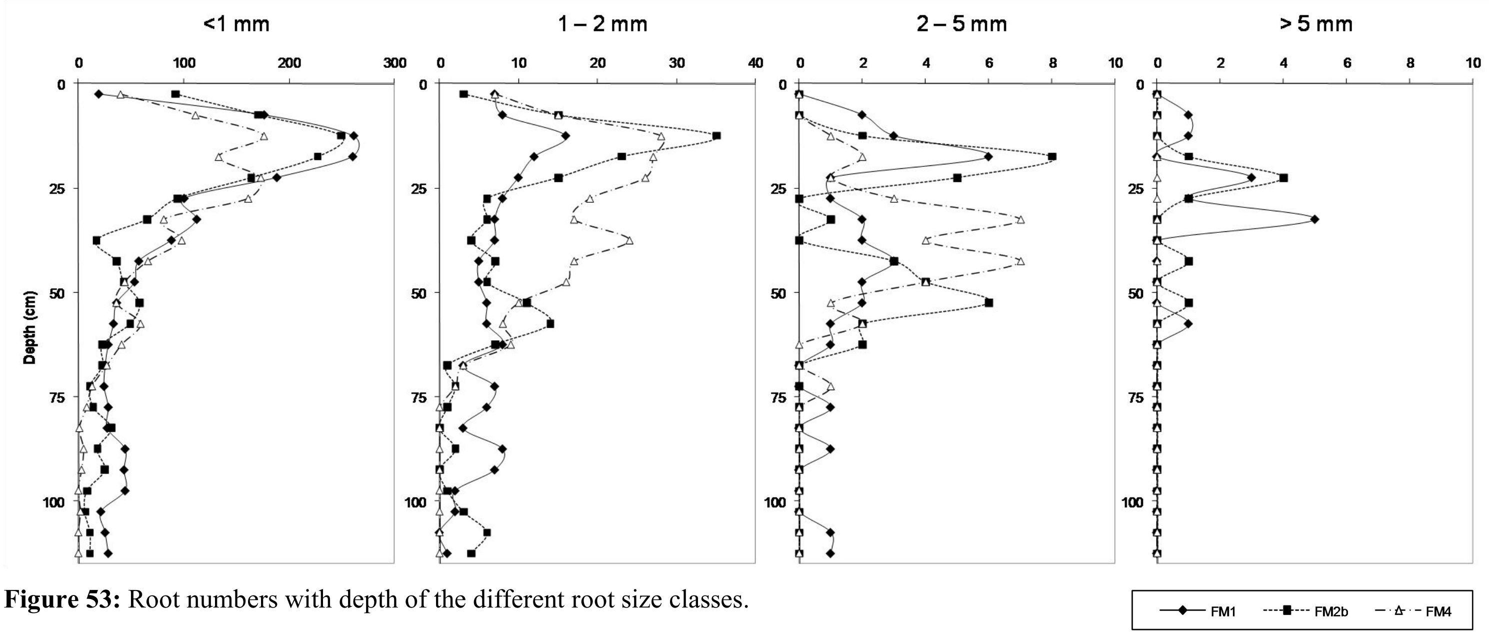

Figure 53: Root numbers with depth of the different root size classes.

Table 31: Total root numbers for the respective soil profiles. Numbers in brackets indicate the percentage of the total root observations for each profile.

	Root numbers				
	< 1mm	1 - 2 mm	2 - 5 mm	> 5mm	Total
FM1	1720	144	30	12	1906
	(90.2)	(7.6)	(1.6)	(0.6)	(100)
FM2b	1446	172	33	8	1659
	(87.2)	(10.3)	(2.0)	(0.5)	(100)
FM4	1278	228	33	0	1539
	(83.0)	(14.8)	(2.1)	(0.0)	(100)

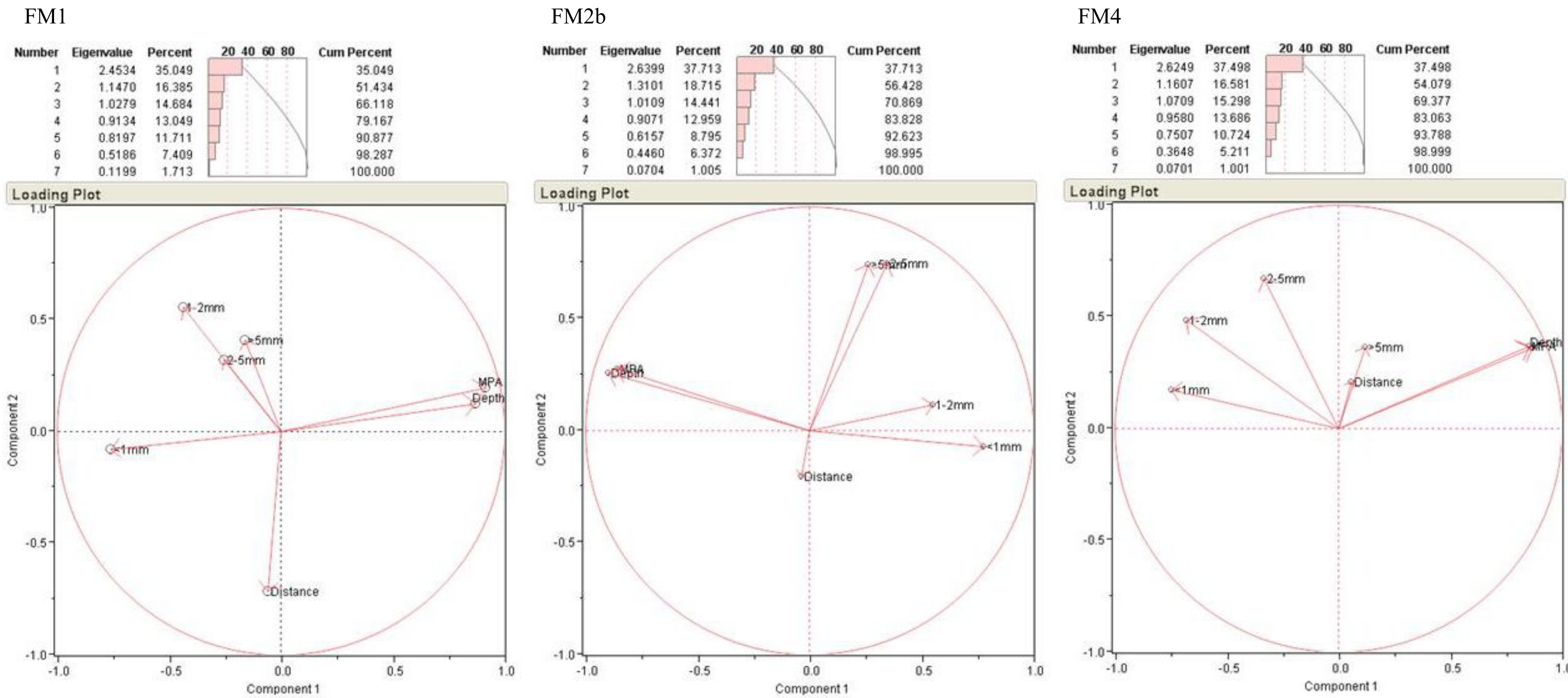

Figure 54: Two-Factor loading plots showing relationships between root size classes, soil penetration resistance. These plots account for 51.4 % 56.4 % and 54.1 % of the variation in the data for FM1, FM2b and FM4 respectively. All profiles have MPa tightly clustered with depth.

Estimation of Plant Available Water

The estimated values of plant available water (PAW) using the upper 1 m of the profile were relatively similar between the profiles with only a small difference estimated between the profiles (Table 32). However, differences were seen in estimations of PAW within the effective root zone (90 % of root observations) due to differing rooting depths. The shallower root distribution of the FM4 profile resulted in this profile having the lowest estimation of PAW within the effective root zone.

Table 32: Estimation of plant available water (PAW)

Profile	PAW (1 m depth) (mm/m)	Depth of 90% root observations (cm)	PAW (90 % roots) (mm)
FM1	122.2	87.5	107.2
FM2*	117.3	-	-
FM2b	123.4	67.5	93.4
FM4	110.3	50	62.3

*No root observations taken at this profile

Multivariate analysis of penetration resistance and root distribution

Two-Factor loading plots describing analysis of root distribution and penetration resistance are shown in Figure 54. These plots account for just over 50% of the variation observed from the different profiles (51.4 % 56.4 % and 54.1 % for FM1, FM2b and FM4 respectively). Table 33 shows there are many significant relationships between the variables measured however most correlations were generally weak. In all plots, penetration resistance (MPa) and depth are tightly clustered together on the loading plots indicating these are strongly related. These also have the strongest correlations of all the analysed factors with positive correlations of 0.86, 0.92 and 0.93 for FM1, FM2b and FM4 respectively. This explains the trend of generally increasing penetration resistance with depth shown in Figure 48. It also shows the dominance of the stronger penetration resistance within the bedrock, as both FM2b and FM4 having a stronger correlation than FM1.

The next strongest correlations were between the fine roots (< 1 mm) and either depth or penetration resistance (MPa). On the loading plots, this root class was generally directly opposing both MPa and depth, signifying a negative relationship. This was supported with negative correlations at all plots (Table 33) indicating that root numbers decline as MPa and / or depth increase. FM1 had a stronger correlation between the fine roots and MPa (-0.58) compared to fine roots and depth (-0.46). This trend was opposite at FM2b with a correlation of -0.49 between fine roots and MPa and -0.58 between fine roots and depth. This helps to highlight the increased abundance of fine roots at depth (> 65 cm) within FM1 as shown in Figure 53. FM4 had the lowest correlations between fine roots and these factors with correlations of -0.46 and -0.43 between depth and MPa respectively. The next strongest correlations occur between the 1 - 2 mm and the < 1 mm root size classes. This relationship was positive indicating that these two root sizes have a tendency to occur together. The correlation between these root sizes strengthens as the observations progress down the slope (0.30, 0.45 and 0.59 for FM1, FM2b and FM4 respectively). This was most likely through the soil structural differences observed between the profiles. A similar, but weaker, relationship was observed between the 2 - 5 mm and 1 - 2 mm roots (correlations of 0.16, 0.19 and 0.34 respectively).

Table 33: Pairwise correlations between root size classes, soil penetration resistance and soil position.

Indices		Correlation coefficient FM1	FM2b	FM4
MPa	Distance	-0.0796	-0.0297*	0.0070n
MPa	Depth	0.8631	0.9218	0.9288
< 1 mm	Distance	0.0875	-0.0835	-0.0824
< 1 mm	Depth	-0.4582	-0.5834	-0.4599
< 1 mm	MPa	-0.5826	-0.4866	-0.4260
1-2 mm	Distance	-0.1067	0.0155n	-0.0503
1-2 mm	Depth	-0.1831	-0.2842	-0.3275
1-2 mm	MPa	-0.2082	-0.2399	-0.3104
1-2 mm	< 1 mm	0.3022	0.4495	0.5869
2-5 mm	Distance	-0.0116n	-0.0777	0.0614
2-5 mm	Depth	-0.1209	-0.1390	-0.1147
2-5 mm	MPa	-0.0979	-0.1355	-0.1277
2-5 mm	< 1 mm	0.1403	0.1551	0.1383
2-5 mm	1-2 mm	0.1555	0.1943	0.3369
> 5 mm	Distance	-0.0492	-0.0062n	0.0767
> 5 mm	Depth	-0.1134	-0.1044	0.0806
> 5 mm	MPa	-0.0871	-0.0869	0.0952
> 5 mm	< 1 mm	0.0186n	0.1041	-0.0274n
> 5 mm	1-2 mm	0.1061	0.0884	-0.0202n
> 5 mm	2-5 mm	-0.0061n	0.3721	-0.0100n

All values are significant (P<0.001) except were indicated with 'n' or '*' which refer to no significance and P<0.05 respectively.

Depth = vertical depth from soil surface

Distance = horizontal distance from vine trunk

MPa = soil penetration resistance

< 1 mm, 1-2 mm, 2-5 mm & > 5 mm = respective root size classes

Vine measurements

The measured vine parameters and associated data are presented in Table 34. FM2 consistently had the highest fruit yield over the three years and was significantly higher ($P<0.05$) than both FM1 and FM4 in all years. Mean vine yield at FM2 ranged from 2.97 – 3.73 kg/vine. FM2b had a similar mean vine yield to FM2 (2.62 – 3.31 kg/vine) and although yields were continually lower than FM2, none were statistically significant. Yield at FM2b was significantly greater ($P<0.05$) than FM1, however was only significantly greater ($P<0.05$) to FM4 in 2009. FM1 was consistently the lowest yielding plot (1.36 – 1.71 kg/vine) and while it was continually significantly lower ($P<0.05$) than both FM2 and FM2b it was not significantly lower than FM4 (1.85 – 2.40 kg/vine) in any year.

Bunch numbers per vine were relatively consistent between plots each season, with only FM1 having a significantly lower ($P<0.05$) number of bunches than FM2 in 2008 and 2009. Variations in yield were therefore mainly due from differences in bunch weight. These followed a similar trend to overall yield, with FM2 and FM2b having significantly higher ($P<0.05$) mean bunch weight than FM1 or FM4. All plots had an increasing trend of yield over the three years, with the average vine yield increasing between 0.35 – 0.76 kg/vine. While this represents an increase in harvestable yield of 0.8 – 1.8 t/ha, the increases were not statistically significant for any plot (statistics not shown).
Pruning weights were highest at FM2 and FM2b. These were generally 1.5 times greater than the pruning weights of either FM1 or FM4. This difference was significantly greater ($P<0.05$) 2007 and 2008.

All plots showed an increase in pruning weight over time, with weights from the outside plots increasing by approximately 2.5 times, with middle plots increasing by 1.5 – 2 times the 2006 value. All plots had significantly higher ($P<0.05$) pruning weight in 2008 than measured in 2006.

Table 34: Vine measurement data from Frogmore Creek Vineyard. Different letters indicate parameter values are significantly different between plots in that year.

Parameter	Plot	2006	2007	2008
Yield:Pruning weight	FM1	6.16 ab	2.41 a	2.02 a
	FM2	3.86 b	3.42 a	2.78 a
	FM2b	5.97 ab	3.37 a	3.01 a
	FM4	7.32 a	4.94 a	3.29 a
Yield (kg/vine)	FM1	1.36 c	1.51 c	1.71 b
	FM2	2.97 a	3.23 a	3.73 a
	FM2b	2.62 ab	2.90 ab	3.31 a
	FM4	1.85 bc	2.18 bc	2.40 b
Yield (t/ha)	FM1	3.24 c	3.59 c	4.07 b
	FM2	7.07 a	7.69 a	8.88 a
	FM2b	6.24 ab	6.90 ab	7.88 a
	FM4	4.40 bc	5.19 bc	5.71 b
Bunch number (bunches/vine)	FM1	28.67 a	24.58 b	27.33 b
	FM2	33.92 a	33.67 a	36.58 a
	FM2b	31.42 a	32.17 ab	34.00 ab
	FM4	32.42 a	30.42 ab	35.33 ab
Av bunch weight (g)	FM1	47.46 b	61.76 c	63.57 b
	FM2	86.51 a	95.27 a	102.19 a
	FM2b	82.44 a	89.39 ab	98.00 a
	FM4	56.83 b	71.58 bc	71.12 b
Pruning weight (kg/vine)	FM1	0.32 b	0.65 b	0.86 b
	FM2	0.82 a	1.00 a	1.36 a
	FM2b	0.56 ab	0.95 a	1.15 a
	FM4	0.31 b	0.49 b	0.76 b
Av. Shoot number (shoots/vine)	FM1	16.83 ab	16.5 b	21.83 b
	FM2	20.75 a	22.92 a	25.75 a
	FM2b	20.58 a	23.00 a	23.83 ab
	FM4	12.75 b	15.75 b	20.25 b
Av. Shoot wt (g)	FM1	18.05 b	40.36 a	39.14 b
	FM2	40.37 a	43.54 a	52.88 a
	FM2b	26.15 b	40.60 a	48.60 a
	FM4	25.74 b	33.12 b	37.66 b

Discussion

Soil properties and soil formation

All soil profiles examined at this vineyard showed the influence of an apron of dolerite colluvium deposited down the slope. This was despite three of the profiles having a substrate of weathering Triassic sandstone. The soil chemical signatures of the soil profiles were also very similar and demonstrate these soils are indeed closely related and that the underlying bedrock has had little influence on soil properties. All soils had a trend of increasing EC and pH with depth, high levels of organic carbon and high levels of exchangeable cations. The most dominant cation was calcium, and was present both on the exchange sites as well as precipitations as free forming pedogenic calcium carbonate. Many subsoil horizons effervesced in the presence of dilute HCl even when calcium carbonate was not clearly visible, indicating that carbonate was also present within the soil matrix. The accumulation of pedogenic calcium carbonate helps explain the increasing trends of both EC and pH with depth, in which the creation of a solution with higher ionic strength and increased pH, by neutralising any free H^+ ions. However, the increase in pH down the profiles did not correlate to an increase in exchangeable calcium. The trends in exchangeable Ca^{2+} seem to be opposed to both the EC and pH trends as well as the observations of calcium carbonate precipitation. This is due to the values of exchangeable Ca^{2+} being a measure of the divalent ion held by the soil exchange complex, whereas both the EC and pH will also be influenced by other factors within the soil and not just the exchange sites. For example, the free carbonate within the profile will influence both these measurements. When analysing the exchangeable Ca^{2+}, the free carbonate was accounted for by undertaking a pre-wash prior to analysis of exchangeable cations as outlined by Method 15C1 (Rayment & Higginson, 1990). This method also uses an alkaline extraction solution to minimise the inclusion of solid phase carbonates.

All profiles had horizons that were sodic, with all but FM2 having at least one horizon with an ESP approaching 10 %. Dolerite is naturally low in sodium, consequently the high level of exchangeable Na^+ within these profiles was attributed to natural additions from rainfall, termed 'cyclic salts', as sodium is a major ion in rainfall in eastern Tasmania (Jackson, 2000). Frequent rainfall or subsequent application of water through irrigation will leach the sodium through the soil profile where it can potentially accumulate in lower horizons. Even though sodic horizons were present, no dispersion was observed from any horizon. This was possibly due to the high levels of pedogenic calcium buffering the soil solution, which minimised the ionic potential between the colloids and the soil solution. As this form of calcium is not held on the exchange sites of the soil, it is not included in the calculation of sodicity and thus the proportion of sodium on the exchange sites would be overestimated. These soils re-enforce the fact that not all soils classified as sodic actually exhibit dispersion (Sumner, 1993).

Organic carbon was high for all profiles with topsoil values all greater than 4 %. Consistent differences can be seen between the profiles, with the upper slope (FM1) having greater organic carbon throughout the profile than the mid-slope (FM2 & FM2b) which in turn have higher values than the lower slope (FM4). The values correspond to the soil colour of each profile, with organic carbon values decreasing as soil colour becomes greyer. The base of FM2b has high organic carbon values signifying a substantial difference in this part of the profile. Coupled with high values of exchangeable Ca^{2+}, Mg^{2+} as well as high ECEC it suggests that this horizon is stratigraphically different to the rest of the profile. It was concluded that this was a truncated remnant horizon of a prior profile now buried by doleritic colluvium. Osok and Doyle (2004) have previously demonstrated the complex stratigraphic history of doleritic soils in south-eastern Tasmania.

The trends of EC and exchangeable Na^+ suggest solute and cation leaching occurs in most profiles as the greatest accumulation of these cations and salts occur in subsoil horizons. Within profile FM1 values increase with depth and highest values occur at the base of the profile, whereas within the other profiles (FM2, FM2b and FM4) highest values occur within the mid subsoil horizons. Values then subsequently decrease in horizons approaching the underlying sandstone bedrock. This suggests preferential water movement and leaching may also occur within these profiles, caused by the interaction of the soil structure and the underlying bedrock. Hardie (2011) demonstrated preferential water movement is a dominant feature of texture contrast soils in south-eastern Tasmania and that many types of preferential flow, e.g. funnel flow and marcopore flow, can occur within the one profile. Even though different soil types were studied at Frogmore Creek, it is highly likely that similar preferential flow pathways are occurring with water being preferentially directed down the cracks between the coarse columnar peds. As the linear shrinkage of these soils was very high, cracks are likely to occur even at moderate soil moisture levels. Therefore it is likely that preferential water movement through by-pass flow can occur in these soils even when soil moisture is moderate. Perching of water may also be occurring at the base of many profiles due to the underlying sandstone bedrock. This would allow dissolution of many soluble salts and allow them to be subsequently leached from the base of the profile. The mottling and dominance of grey colours of lower subsoil horizons observed at FM2, FM2b and FM4 supports this and indicates wetness and possibly lateral water movement at the base of these profiles.

The soil profiles observed in this study correlate well with the soil mapping undertaken by Chilvers (1998). All were dark coloured, reactive clay soils derived from dolerite. The upper three profiles all classified as Black Vertosols (Isbell, 1996) with the lowest profile (FM4) classified as a Grey Vertosol (Isbell, 1996). This contrasts with the CSIRO's 1960's regional reconnaissance soil maps, recently re-published by Spanswick and Kidd (2000a), which show the upper slopes mapped as 'Brown soils on Dolerite' and lower slopes as 'Podzols and Podzolic Soils on Sandstone'. While the lower slopes were underlain by sandstone, the soil above was a strongly vertic clay rather than a texture contrasting podzolic profile suggesting a mafic rather than siliceous parent material. A reconnaissance of the surrounding area showed that the soils on the adjacent hillslopes to the south of the studied site were Triassic sandstone derived Podosols (Isbell, 1996). This discrepancy in soil type was expected as the map sheets produced by Spandswick and Kidd (2000a, 2000b) were published at broad scale (1:100,000). The soil boundaries were originally undertaken by Loveday (1955) and Dimmock (1957) and many soil boundaries were placed using aerial photograph interpretation with limited local mapping on the ground. Differences could also be expected as the study area was situated at the boundary of two map sheets and the fact that these map sheets do not have aligned boundaries. This suggests that there was a good reason for the later mapping by Dimmock (1957) not to match the earlier boundary position meaning that it is less likely that the lower slopes would be Podzolics on sandstone. The current soil maps (Spandswick and Kidd, 2000a, 200b) were produced to correlate mapping units to the Australian Soil Classification System (Isbell, 1996) and no new field observations were undertaken. Therefore the soil boundaries are reproductions of the earlier mapping (Loveday, 1955; Dimmock, 1957). Chilvers (1998) however, produced a detailed scale map (1:5,500) based on many soil observations at the site. It is therefore not surprising that the current study matches the soil pattern he delineated. This shows the importance of using soil maps within the constraints of their scale, with broad scale maps used for regional and catchment based decisions. Detailed investigations of landscape attributes and processes are then required prior to specific viticultural investments being undertaken.

Influence of soil properties on root growth and distribution

Similar trends of vertical root distribution were recorded for all soil profiles. All profiles had the highest root abundance in the upper 10 – 30 cm of the soil with root numbers declining below this depth. Low root abundance was also recorded in the surface soil of all profiles (0 – 5 cm) which was also reported at previous sites. In previous chapters it was assumed that the surface layer was less favourable to root growth due to increased soil temperature, increased evaporation and decreased moisture availability. At the current vineyard, the high weed presence along the vine row may also have reduced vine root growth in the upper soil profile due to increased competition for nutrients and moisture in the upper profile. The lack of near surface roots in grapevines has previously been suggested as an evolutionary trait developed through intensive competition with other plant species (Morano, 1995 cited in Smart *et al* 2006) and is another possible explanation for the reduction of vine roots observed within this part of the profile.

The decrease in root growth within the lower subsoil horizons was similar to the vertical distribution of organic carbon, exchangeable Ca^{2+} and exchangeable K^{+} which all decreased with depth. Soil pH, electrical conductivity (EC), exchangeable Na^+ and penetration resistance all increased with depth and are thus inverse of the observed root growth. While most of these observations were similar to profiles discussed in other chapters, the suggested relationship between root growth and soil pH is opposite within the currently studied profiles. This suggests the high pH of these soils (pHw > 8) may be inhibitory to root growth. Previous studies have demonstrated that high soil pH (pHw > 8.3) can reduce vine growth (Davidson, 1991; Gelat, 1996; Saayman, 1981) thus it is possible that high pH caused inhibition of root growth in the subsoil horizons. However, within the current study, the high soil pH occurred in association with increasing soil depth. Therefore the influence of soil depth cannot be discounted as the cause of reduced vine root growth. As similar trends of declining root growth with depth were recorded in other sites where the soil pH trend was both acidic (Chapter 4) or neutral (Chapter 5) the reduction in root growth with depth observed within in the dolerite derived soil to be due to soil depth rather than the alkaline pH trend.

While subtle differences occur between the chemistry of the soil profiles, all profiles had high soil fertility and it is unlikely that the small chemical differences were enough to cause the observed differences in root growth and distribution. For example, it could be argued that the lower levels of exchangeable Ca^{2+} and organic carbon could be contributing to the reduction in root growth at FM4. However, the values within this profile are still quite high and unlikely to be deficient e.g exchangeable Ca^{2+} greater than 15 cmol(+)/kg. Conversely, both FM4 and FM1 have similar exchangeable K^+ values at depth, but there were dramatic differences in root distribution. Instead it was more likely that differences in root distribution were due to differences in penetration resistance, soil structure, and potentially differences in soil moisture as these are spatially concordant in the profiles.

Increasing soil penetration resistance appeared to have a negative impact on root growth. This was particularly apparent with the distribution of fine roots (< 1 mm) which had a correlation coefficient of approximately -0.5 with soil penetration resistance (MPa) in all soil profiles (-0.58, -0.49 & -0.43 for FM1, FM2b and FM4 respectively). However, as penetration resistance (MPa) was strongly correlated with soil depth in all profiles (coefficient of approx 0.9), the relationship observed between roots and MPa could consequently be a function of increasing soil depth. This was reflected in analysis of fine root distribution that had similar correlation coefficients against soil depth as recorded against MPa. Interestingly, the highest subsoil MPa values were observed in the profile with highest subsoil root numbers (FM1). Clark (2008) may provide an explanation for this observation as he established that a gradual increase in soil strength gave better root penetration of strong layers than an abrupt change. While that study was done for different rice cultivars, the steady increase of MPa with depth measured at FM1 may mean the vine roots can grow through tighter soil when compared to the rapid change of MPa observed at FM2b and FM4. While significant correlations between root growth and MPa were measured, most of the MPa values recorded were also below 2 MPa which is the accepted critical limit for root growth (Van Huyssteen, 1983; Myburgh *et al*, 1996) and may mean that the measured MPa values may not be as important as initially thought. However, the MPa was measured during late winter and the soil had relatively high soil moisture, reducing the MPa values being recorded. Higher MPa values may therefore be present in the soil at different times of the year that could restrict root growth.

The profiles in the mid and upper slopes (FM2b, FM1) had highest root counts while the lower slope had the lowest root count (FM4). This reflects the estimations of plant available water (PAW) of these profiles (Table 11) with FM4 having slightly lower estimated PAW than at either FM2b or FM1. The role of soil moisture controlling root growth is well supported in the literature. David and Payne (1970) highlighted the role of soil water in root growth, with higher soil strengths as the soil dried. These higher strengths caused the root system to distort. More recently Lakso (2003) demonstrated that irrigated and unirrigated grapevines produce similar numbers of new roots during a wet year. In a dry year however, the unirrigated vines produced only about one third as many roots. This supports Conradie *et al* (2002) who found root distribution was mostly affected by soil moisture, compact layers and the stone content and not necessarily by geology or parent material. In the current study, the reactive shrink-swell clays could also be causing distortion of root distribution by confining roots to the cracks between structural units. The cracks, or planar pores, are a zone of weakness that the roots can exploit. As the soil dries and the cracks open, the outer layer of soil on the crack face is able to preferentially dry compared to the rest of the soil matrix, thus making it even harder for roots to penetrate and restricting root growth to within these zones. During the wetting phase, the expansion of the soil exerts pressure on the roots flattening and distorting their shape (Figure 45). Any root flattening will alter the surface area to volume ratio of the roots and possibly be a cause of reduced root function. If the pressure is large enough, then roots may be macerated or even be sheared (pruned). If these cycles occur frequently then the roots have a limited timeframe to grow before being pruned off, reducing their size. Thus roots in these zones of frequent shrink-swell activity may be more prone to having fine roots.

In all profiles studied, the distribution of the different root size classes closely matched the size and degree of development of the soil structure. This was particularly evident within the horizontal distribution with largest roots were mainly found in the cracks between the primary structural units and only finer roots (< 2 mm) were found in between cracks of the secondary structure. Thus the size of structural unit was important. At FM4, the primary structure was coarser than the other observed profiles and the fine root distribution closely matched these cracking patterns meaning there were greater constraints to root growth within this profile. The restriction of most root growth to cracks between structural units within the subsoil was similar to the restrictions recorded within the subsoils of the Kurosol profiles in Chapter 4 e.g Kurosol-Burnt, Kurosol-Scalped and Kurosol-Sodic. However, in the case of FM4, the restriction was purely due to physical restrictions caused by the subsoil structure. Therefore vine roots growing within FM4 will also have less volume to exploit and less access to stored nutrients and moisture.

At FM4 it is hypothesised that the lenticular structure of the B23 and B24 has led to the lack of observed root growth. It is clear, based on this structure type, that these horizons undergo more frequent shrink-swell cycles leading to continual root pruning and death. The frequency of wetting and drying cycles at FM4 could explain why no large roots (> 5 mm) were observed within this profile. The lack of a self-mulching topsoil allows the cracks to extend to the surface as thus exacerbate the drying and shrinking process. Similar reactive clays occurred in the subsoils at the other profiles, however the presence of a self-mulching topsoil at those profiles meant cracks are in part in-filled with topsoil (Figure 44) and the rate of desiccation potentially decreased. Within these profiles (FM2b and FM1) a slight increase in root growth was recorded at depth (80 – 100 cm) associated with the lower depth of the structural cracks. This was most evident within the fine roots of both profiles and indicates that this part of the profile had more favourable conditions for root growth. This was highly visible at FM1 where a 'hot-spot' of growth was observed at the bottom left corner of Figure 49a. Within these profiles it was assumed that these zones had greater available soil moisture than horizons immediately higher, or horizons at corresponding depths within FM4. This could be partly through reduced desiccation from the topsoil in-fill, but also could be due to preferential water movement concentrating moisture at the base of the cracks as demonstrated by Hardie (2011).

Therefore differences in soil moisture within preferential pathways through the soil profile appear to be the main factor that influenced root growth and distribution. The lack of root growth within the upper 0 – 5 cm also seems to relate to decreased moisture availability, both through increased evaporation and also increased weed competition. The increase in root growth at the base of structural cracks may also be due to increased availability of moisture provided via preferential water flow in the profile (Hardie, 2011). This preferential flow may be aided by the porous topsoil observed in-filling these vertical cracks. Both assumptions need to be confirmed through further research as the study of available soil moisture and its preferential movement were not the focus of this study. However it is now clear that measurement of soil moisture needs to occur within at least three depths within these profiles corresponding to 1) the surface horizons (0 – 5 cm); 2) the near surface horizons (10 – 30 cm) and 3) the lower depth of structural cracks (in this case 80 – 100 cm).

Influence of root distribution and root function on vine growth

In contrast to the previous chapters, significant differences in both vine growth and fruit yield were not related to differences in soil nutrition or to the total abundance of vine roots. While FM4 was the shallowest profile with the lowest abundance of roots and the lowest vine vigour, its vigour was not statistically lower to FM1 which had the highest root abundance. Similar high root numbers were observed within the middle of the block, but these plots (FM2 & FM2b) had significantly higher vine vigour and fruit yield than both FM1 and FM4. This suggests differing root efficiency and function is occurring between the profiles, and root function has previously been shown to be important for both nutrient and water uptake of grapevines (Richards, 1983; Cass, 2004).

At FM4, the coarser primary structure and the stronger association between root growth and cracking patterns meant there were greater restrictions to root growth than other profiles. Root restriction has been demonstrated to significantly reduce the above ground growth (leaf and shoot dry weight, leaf area and photosynthesis) of pot grown grapevines (Zhang and Bravdo, 2001) and it is likely to be the cause of the reduction in vine growth and fruit yield at FM4. Zhang and Bravdo (2001) also demonstrated that increasing root restriction decreased the abundance of larger root sizes. This may explain the lack of coarse roots (> 5 mm) within this profile. The estimation of root zone plant available water was also lowest within FM4, therefore vines at this plot not only have less soil volume to exploit but also potentially less access to stored nutrients through reduced soil moisture. The lack of a self-mulching topsoil at this profile would also result in greater desiccation of moisture and greater crack expansion from this soil than at the other profiles as the cracks are more readily opened to the soil surface. As most of the root growth occurred within these cracks this would also decrease the root-soil contact leading to reduced root efficiency. In addition, Huang *et al* (2005) demonstrated that roots exposed to drying soil also exhibited increased membrane leakage and reduced nitrogen content, thus impairing the ability to uptake nutrients.

The high root abundance but lower vine growth and fruit yield at FM1 suggests this profile also had reduced root efficiency. However the cause of this reduction was unclear as this profile was considered to have the most favourable conditions for growth due to it being the deepest profile with the deepest root growth and had the highest estimated PAW, within both the soil profile and the root zone. It is thought that this profile undergoes more frequent cycles of shrink-swell activity leading to increased root mortality. The lenticular structure with slickensides coupled with high measurement of linear shrinkage indicates many horizons did have a strong shrink-swell nature that could result in increased root mortality. The vine would then have to continually re-grow roots resulting in greater requirement of resources portioned to root growth.

The possibility also exists that the reduced growth at FM1 may have resulted from increased weed competition during initial vine establishment as the organic management of the vineyard often resulted in variations in weed abundance across the vineyard (Scherer, pers comm.). Young vines are particularly susceptible to weed competition (Due *et al*, 1999) and the growth of these vines could therefore be suppressed. Examples of suppressed vine growth were readily observed coinciding to rows where overhead irrigation is installed. This can be clearly demonstrated in the detailed infra-red image of individual vine data (Figure 39). The overhead irrigation was used exclusively during vineyard establishment and resulted in excess grass growth within these rows (Scherer, pers comm.). Even though the infra-red image was taken over five years later, the reduction in vine growth was still apparent. It was for this reason that these rows were excluded from measurement within this study. As the influence of weed competition was still evident many years after their direct influence was removed, it is highly possible that the reduction in vine growth at FM1 occurred through historical factors that were not able to be measured within the current study.

The mid-slope plots (FM2 and FM2b) consistently had the highest pruning weights and fruit yield than the other two plots. The greater shoot number, higher average cane weight and higher average bunch weight all suggest these vines had greater access to moisture than those at either FM1 or FM4. Vines with increased access to soil moisture have been demonstrated to have increased vegetative growth (Peterlunger, 2005) and that stem water potential, needed for cell expansion, is determined by soil water availability

(Van Leeuwen and Seguin, 1994; Van Leeuwen *et al*, 2006). Shoot numbers are also greater through increased moisture uptake (Santos *et al*, 2003) and so the greater numbers of shoots and higher cane weight at FM2 and FM2b were likely to be caused through increase soil moisture availability. Differences in berry size and berry weight have also been demonstrated to be influenced through of soil moisture (Hunter *et al*, 2006; Ojeda *et al*, 2001; Reynolds *et al*, 2007), with increased soil moisture increasing yield through increased berry weight (Reynolds *et al*, 2007). This further suggests that these profiles had increased availability of soil moisture. This was despite these profiles having a similar estimation of plant available water (PAW) and similar root numbers to FM1. This suggests that the efficiency of the roots at FM2 and FM2b was greater than those at FM1. While these profiles had similar PAW estimations it is likely that the topographical position of FM2 and FM2b may increase the availability of soil moisture. Both profiles were situated slightly below the break in slope and the interaction of the underlying sandstone bedrock may cause the lateral flow of water to be closer to the surface at this part of the landscape. This is similar to the natural 'belly' of the slope as shown by Wilson (1998) in the Burgundy region of France. As soil moisture was not measured as part of this study, further research will be required to confirm this suggested explanation.

While differences in vine growth and fruit yield were observed in all plots between vintages, the relationship between the plots was relatively consistent. This suggests that the patterns of within-vineyard variation are comparatively stable from one year to the next. This implies that the underlying cause of vineyard variability is also consistent between seasons, promoting soil type and topographic differences across the site as the main cause. This is consistent with Van Leeuwen *et al* (2006) who concluded that the relative intra-block distribution of vine water status has good stability over the years. Rawson (2000) also demonstrated that differences in vine growth and quality was reliably associated with different soil types.

The measurements of vine vigour were comparable with the infra-red image of plant cell density. Both pruning weights and the infra-red image demonstrated that the middle of the block was indeed the most vigorous (plots FM2 and FM2b), with both upper (FM1) and lower slope (FM4) having lower vigour. This relationship was expected as previous studies have demonstrated that infra-red spectral readings are able to be correlated with vine vigour (Bramley and Hamilton, 2004; Wells, 2011). While the trends between the infra-red image and the field measurements were similar, the infra-red image (taken in 2006) infers a vigour difference between plots FM1 and FM4. However, the corresponding 2006 field measurements show the pruning weights of these plots to be almost identical (0.32 kg/vine and 0.31 kg/vine respectively). This similarity only occurred in 2006 and the measurements from later years did show FM4 to have consistently lower vigour than FM1. However, while FM4 did have lower pruning weights than FM1 in both 2007 and 2008, the differences were not statistically significant. A similar relationship was observed between FM2 and FM2b, with FM2 consistently having the highest pruning weight in all years, but was not statistically different in any year. The difference observed between the 2006 field measurements and the infra-red image in 2006 could be due to the infra-red image being based on plant cell densities of the leaves, rather than woody growth (which was measured at pruning). While significant differences in cane weights were recorded across the vineyard block, all the plots had average cane weights of approximately 30 – 40 grams each year. This indicates that this vineyard block had mainly moderate vine vigour (Smart and Robinson, 1991) in which variation of vigour across the block was smaller than at the other vineyards studied.

Conclusions

The soil types within this study block were relatively fertile and had many similar pedological characteristics. They all showed strong influence from carbonate rich mafic dolerite colluvium despite three of the four profiles overlying siliceous substrates of weathered Triassic sandstone. This re-enforces the role of colluvial hillslope processes in soil distribution in the Tasmanian landscape. It clearly shows that soils on a hillslope are not always related to the underlying bedrock that are shown on regional geological maps and are often used as a tool for site selection. While all soils had similar Australian Soil Classification and soil chemical trends, differences in root growth and vine growth existed between sites. Soil structure was shown to influence root distribution by restricting root growth to within cracks, particularly vertical cracks formed between coarse columnar and prismatic peds. The vertic nature of the profiles meant that these vertical cracks were defined zones of weakness within the soil in which the lowest measurements of soil penetration resistance were observed. They also appear to be pathways for preferential flow of soil water, and hence nutrients.

It is concluded that reduced vine growth and fruit yield occurred when the structural units were coarse due to a reduced availability of soil moisture to the roots. This was caused by the physical restriction of root distribution resulting in parts of the soil profile being unavailable for root access as well as increased desiccation of roots and reduced root-soil contact when the soil dried and cracked. Vine growth and fruit yield variation was associated with the break in slope within the studied block, which was attributed to increased moisture availability due to the underlying bedrock concentrating water moving through the landscape at this topographical position. Any increase in soil moisture would enable the vine roots to have greater efficiency in the uptake of required nutrients. As soil moisture was not measured during this study, further measurement of soil moisture as it relates to the root zone is required to confirm these assumptions. As well as measurement of soil moisture spatially within the landscape, detailed measurement of soil moisture also needs to occur spatially within the soil profile. This should occur at near surface horizons (10 – 30 cm) as well as measurement at depths corresponding to the base of structural formed, inter-aggregate cracks. Undertaking measurements within the surface horizons (0 – 5 cm) would also determine if the lack of root growth within this layer was due to limited soil moisture.

7. Vine growth and yield on a soil catena formed from differing parent materials

Introduction

Throughout Tasmania the distribution of soil and underlying lithology is highly varied in which changes can occur across small distances. This often results in highly diverse soil types located within close proximity of each other. In a viticultural context, this means that soil properties are not homogeneous across the vineyard or even within a management block. Therefore vineyard management often needs to deal with a variety of soil types that can result in considerable differences in vine growth and yield. Understanding the role that these different soils and their properties have on influencing vine growth is therefore a critical part of the site selection process. Awareness of how variable production can be within vineyards is only now starting to be understood (Bramley and Lamb, 2003; Bramley and Hamilton, 2004).

This chapter aims to investigate the variation in soil type within a single vineyard row, and how this influences vineyard production. It aims to build on the results of previous chapters with the catena of soils selected reflecting similar soil properties. The catena consists of a dolerite derived soil (similar to Chapter 6), soils from Permian sediments (similar properties to Chapter 4) and soil from recent alluvial deposits. The role of soil thickness (as outlined in Chapter 5) will also be discussed.

General Site description

Location

This study site was established at Meehans Vineyard in southern Tasmania. This vineyard was located in the Coal River Valley Wine Region in southern Tasmania (42°52' S, 147°25' E).

Geology and topography

The geology underlying most of the studied area was Jurassic dolerite and related rocks. This graded into colluvium and alluvial sediments at the lower end of the catena. Figure 62 shows a cross-section of the topography and underlying lithology of the study site.

Existing soil maps

The vineyard was covered by the Hobart 1:100,000 scale Reconnaissance Soil Map (Spandswick and Kidd, 2000a). This indicates that the soils within the studied transect were 'Brown soils on dolerite' and all the studied soils were contained within the one mapping unit (Figure 55).

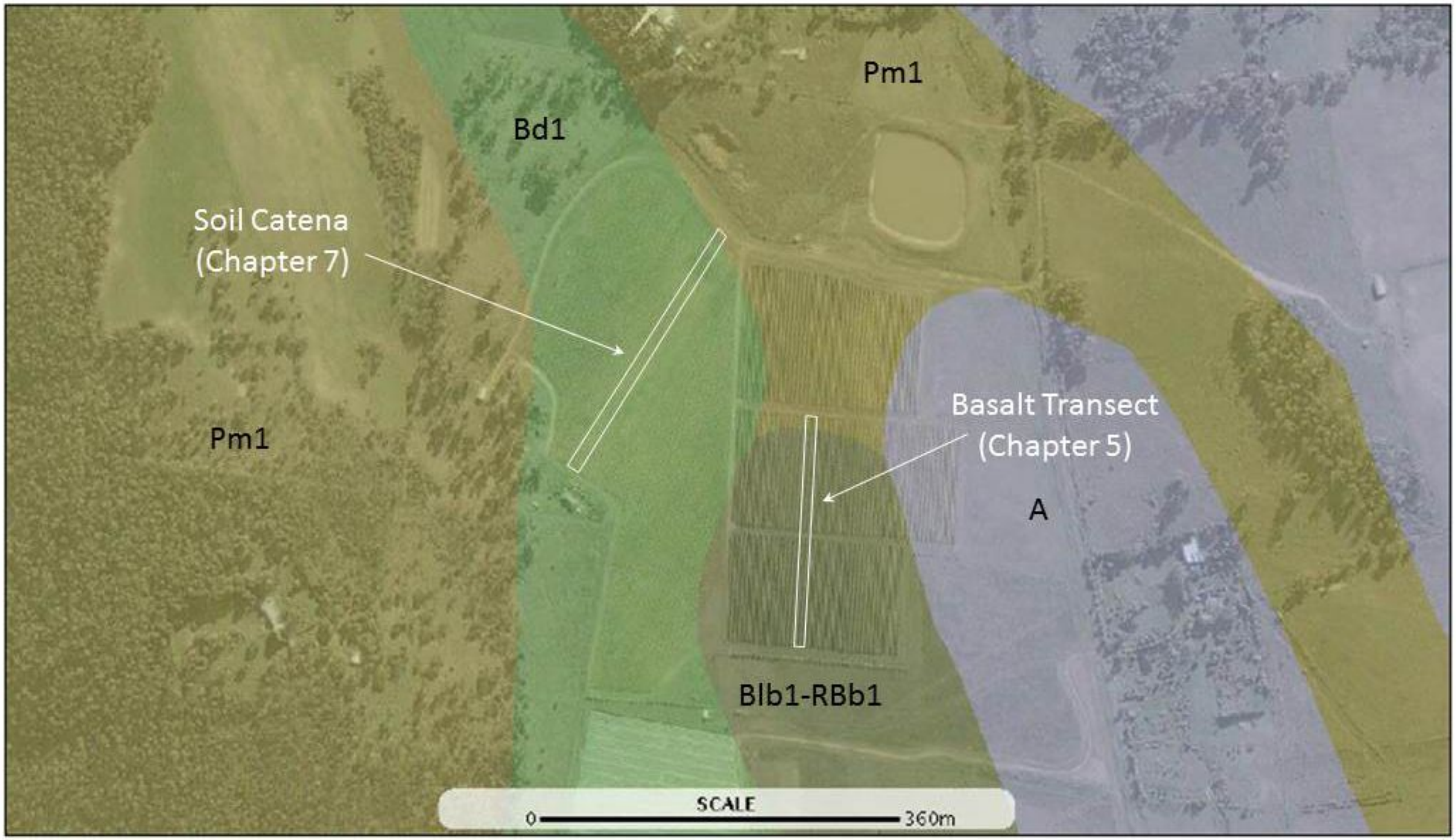

Figure 55: 1:100 000 soil map of the region (Spandwick and Kidd, 2000a)

Key to Soil codes:

Pm1 – Podzolics on mudstone

Bd1 – Brown soils on dolerite

Blb1-RBb1 – Black soils on basalt and red-brown soils on basalt

A – Miscellaneous alluvial soils

Individual site layout

Four plots were established by identifying different soil-landscape features. They occurred as a transect along one vineyard row within a block of own-rooted *Vitis Vinifera* cv Pinot Noir (clone 114) planted in 1999. The location of the individual plots in respect to topography is shown in Figure 56. Rows had a southwest-northeast orientation with a row and vine spacing of 2.5 m and 1.2 m respectively. Vines were pruned to two canes on a VSP trellis and were drip irrigated. All vines received similar management within each block and were harvested on the same day each year.

Climate background at site

Monthly rainfall was determined using figures obtained from the Bureau of Meteorology weather station situated at Hobart Airport (station number 094008) which was situated 7 km to the west of the vineyard. Average annual rainfall for the region was 500 mm/yr with slight winter dominance although distribution is relatively consistent throughout the year. Both the 2006-07 and 2007-08 seasons had below average rainfall although rainfall during the summer months (Dec – Feb) was generally higher than normal (Figure 25). The 2005-06 season had average annual rainfall however this dominantly occurred during winter, with the remaining months receiving below average rainfall. The average maximum monthly temperature is shown in Figure 26, and shows that temperatures were consistent between the studied years. The average monthly temperature was slightly above the long-term average in all years (Table 20).

Results

Remote sensing

The EM38 survey of the catena (Figure 56) was undertaken in 2007. This demonstrated that each of the four profiles were located in areas of contrasting apparent conductivities (ECa). Profile M1 had high ECa in both the horizontal and vertical dipoles indicating that the entire profile influenced ECa values. At profile M2, higher horizontal dipole ECa was recorded than vertical dipole suggesting that the surface soil had higher salt load, or higher soil moisture than deeper in the profile. The surface ECa at M2 was the highest value recorded throughout the survey. This contrasted with M4 that had low ECa within the surface layers but high ECa within lower soil horizons (vertical dipole). Profile M3 had the lowest ECa of all the profiles at all depths.

The aerial vigour map shows that the plant cell density (PCD) varied across the vineyard block (Figure 57). This image was taken in 2009. The ends of the block had mainly high PCD values (blue) indicating high vigour with the middle of the block having moderate vigour (green/yellow). According to this image, profile M4 was situated within the highest vigour and M2 within the lowest vigour. Both M1 and M3 had similar PCD values and indicated they were of moderate to high vigour. The relationship between variation in ECa and PCD was low.

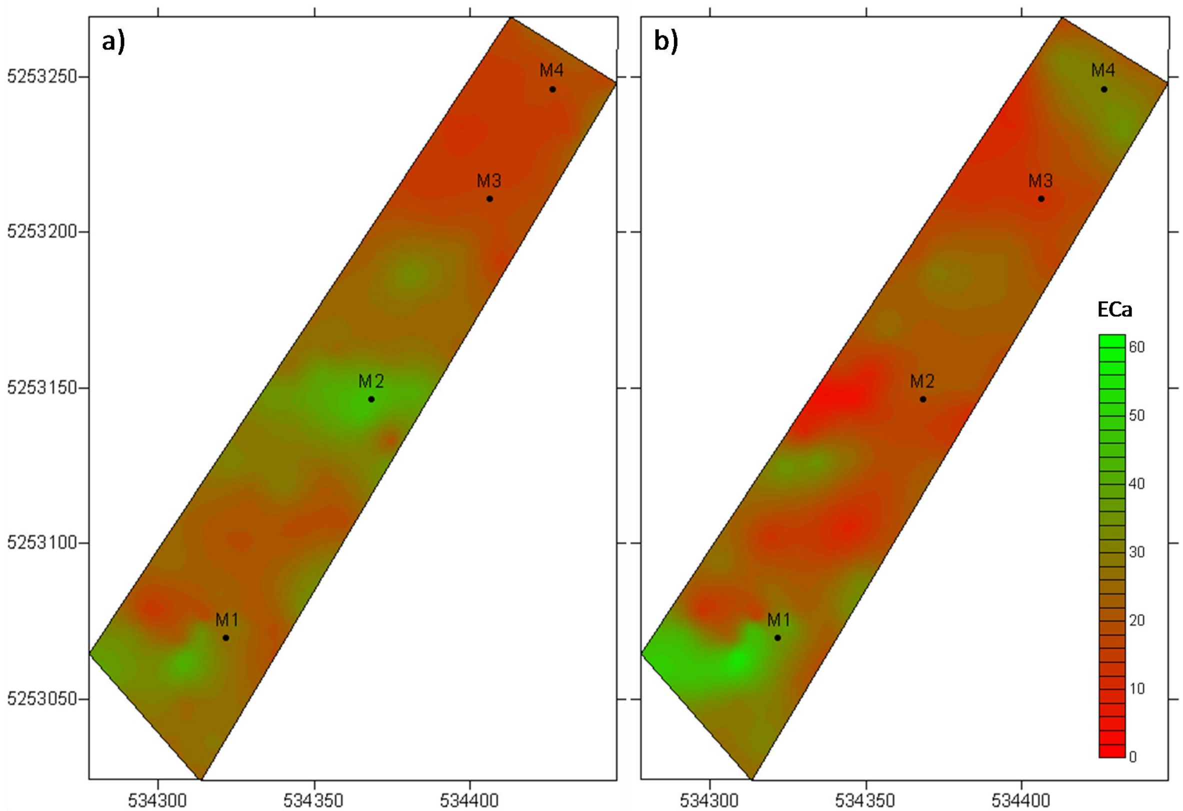

Figure 56: EM38 survey showing effective conductivity of the soils within the catena. Images are (a) horizontal dipole and (b) vertical dipole. Survey was undertaken in 2007

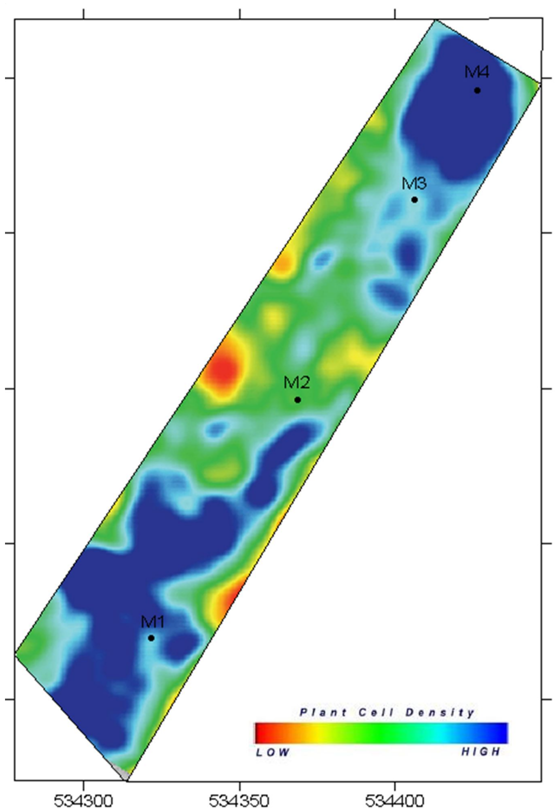

Figure 57: Infra-red image of plant cell density of the catena. Blue colours indicate high plant cell density and red colours indicate low plant cell density. This image was taken in 2009.

Table 35: Soil Classification summary

Soil Profile	Order	Suborder	Great Group	Subgroup	Family criteria					
					A horizon thickness	Gravel (surface and A1)	A1 Horizon texture	Max clay content of B horizon*	Soil depth	Slope angle (%)
M1	VE	AE	GS	BP	C	E	O	O	W	10
M2	SO	AD	ES	AH	A	E	L	O	V	11
M3	SO	AB	ES	AH	B	E	L	O	V	3
M4	SO	AB	ES	AH	B	E	L	O	V	6

*estimated from field texture

Key to Classification codes:

AB – Brown

AD – Grey

AE – Black

AH – Eutrophic

BP – Endohypersodic

ES – Subnatric

GS – Epipedal

SO – Sodosol

VE – Vertosol

A – Thin (< 0.1 m)

B – Medium (0.1 – 0.3 m)

C – Thick (0.3 – 0.6 m)

E – non-gravelly (< 2 %)

L – Loamy (SL-L, 10 – 20 % clay)

O – Clayey (LC-MC-HC, > 35 % clay)

V – Moderate (0.5 - < 1.0 m)

W – Deep (1.0 - < 1.5 m)

Summary soil descriptions

Soil profile M1 was formed from dolerite colluvium and was located on a gently waning mid-slope at the upper most elevation of the study area (Figure 62). This soil had a gradational clay profile consisting of dark coloured clay loam topsoil horizons overlying greyish and olive brown light to medium clay subsoils (Figure 58). This in turn overlay a gritty sandy clay which was similar to the 'mealy' horizon described by Osok and Doyle (2004). This indicates that the base of the profile was formed from weathering dolerite material and most likely formed in place. While the topsoil was dominantly a clay loam, it also had a slightly sandy feel, however this was insufficient to classify the texture as a sandy clay loam. Soil structure dominantly consisted of coarse (50 – 100 mm) prismatic structure. Within the upper subsoil this parted to moderately developed angular blocky structure, whereas the secondary structure became more lenticular at depths below 60 cm. Surface soil structure was moderately developed fine and medium (5 – 20 mm) subangular blocky structure. Distinct dark coloured clay skins of topsoil material were observed lining the cracks of the primary structure. Dispersed dolerite fragments occurred at depths below 35 cm. This profile is classified, according to the Australian Soil Classification (Isbell,1996) as an Endohypersodic, Epipedal Black Vertosol (Table 35).

Soil profile M2 was located below M1 on a moderately sloping waning mid to lower slope. It classified as an Eutrophic, Subnatric, Grey Sodosol (Isbell, 1996). This soil had a texture-contrast profile consisting of a thin greyish brown sandy loam topsoil overlying dark greyish brown light clay subsoil horizons (Figure 59). These subsoils generally had common dark yellowish brown mottles throughout. A stratified sandy material occurred at depths below 60 cm. While the underlying geology was previously mapped as Jurassic dolerite and related rocks (Forsyth, 1975) it was concluded that only the upper horizons were likely to be derived from dolerite colluvium with the underlying sandy fill a possible colluvial fan deposit from the surrounding Permian interbedded siltstone and sandstone hillslopes (S. Forsyth, pers. comms., Figure 62). This was supported with the occurrence of subangular sandstone and siltstone coarse fragments within the subsoil horizons. The topsoil of this profile had moderately developed, fine to medium (5 – 20 mm) polyhedral structure and overlay moderately developed coarse to very coarse (100 – 200 mm) columnar structure within the subsoil. The cracks between these primary peds were filled with sandy topsoil material. The columns parted to weakly developed medium-coarse (20 – 50 mm) prismatic structure.

Soil profile M3 was located on a gently sloping waning lower slope and was formed from a mixture of dolerite colluvium overlying sandy fan deposits similar to profile M2. This profile had a similar texture-contrast profile to M2; consisting of a thin greyish brown sandy loam topsoil overlying olive brown light clay subsoils (Figure 60). At this profile the stratified sandy material occurred at depths below 75 cm. Soil structure was also similar to M2 with coarse-very coarse prismatic structure dominating throughout the subsoil, with the primary cracks filled with sandy topsoil. While the structure of the subsoil was described as prismatic, it was assumed that the structure was originally columnar however the rounded tops of the columns had been removed due to mechanical cultivation. The classification of this profile was also similar to M2; Eutrophic, Subnatric, Grey Sodosol (Isbell, 1996).

Soil profile M4 was located at the lower slope of the catena. It was formed from a mixture of materials ranging from dolerite colluvium, sandy fan deposits and previous clayey alluvial deposits. The upper horizons of this profile had features similar to both M2 and M3, being texture-contrast with greyish brown sandy loam topsoil overlying olive brown subsoils (Figure 61). The main difference of this profile was the inclusion of a buried clayey alluvial derived horizon that was present below 108 cm. A stone-line was present at the base of the B23 (between 92 – 108 cm) indicating that the material above 108 cm to be distinct from the horizons below. These lower horizons had higher clay content and weaker consistence demonstrating a marked difference to the material above. A zone of carbonate accumulation occurred between 132 – 156 cm and this horizon also had common to many vine roots growing within it.

Figure 58: Soil profile M1

showing dark mafic materials overlying brown ‘mealy’ materials at depth (> 145 cm). Abundant root growth can clearly be within the cracks of the strongly developed prismatic structure.mk

Figure 59: Soil profile M2. A texture-contrast profile consisting of greyish brown sandy loam topsoil overlying dark greyish brown light clay subsoil. Lightly coloured stratified sandy material can be seen below 60 cm. Roots were constrained to within the subsoil to zones of weakness between coarse columnar peds.

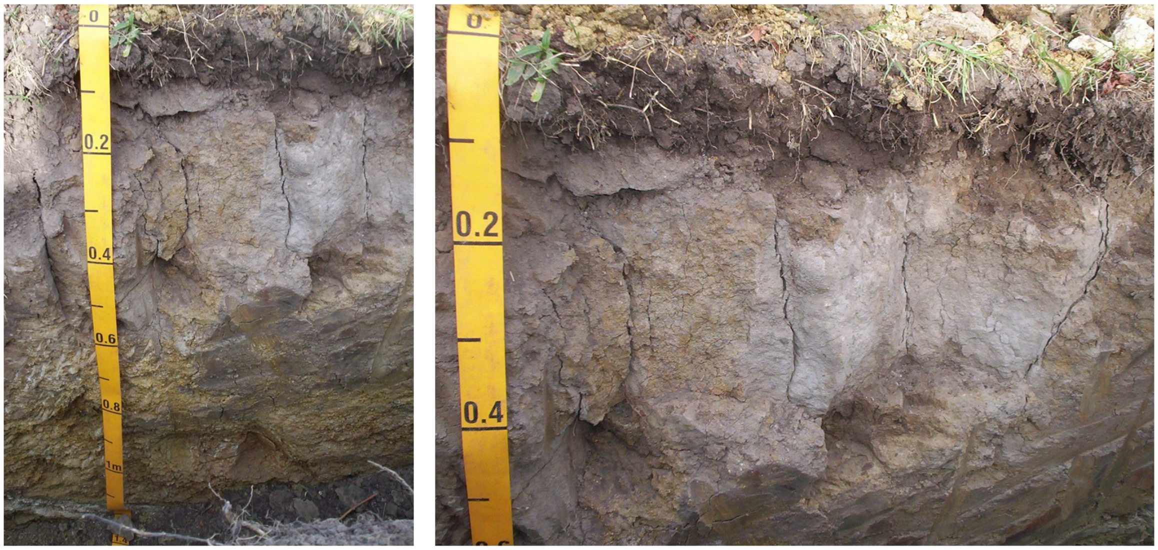

Figure 60: Soil profile M3. Showing similar profile features to M2. The very coarse columnar structure within the subsoil has intervening cracks filled with sandy material. Yellowish sandy stratified material can be seen below 75 cm.

Figure 61: Soil profile M4. The upper profile (< 108 cm) had horizons similar to profiles M2 and M3. At depths deeper than 108 cm, a weak clayey matrix occurred with a zone of carbonate accumulation. A stone-line at 92 – 108 cm separated the two materials.

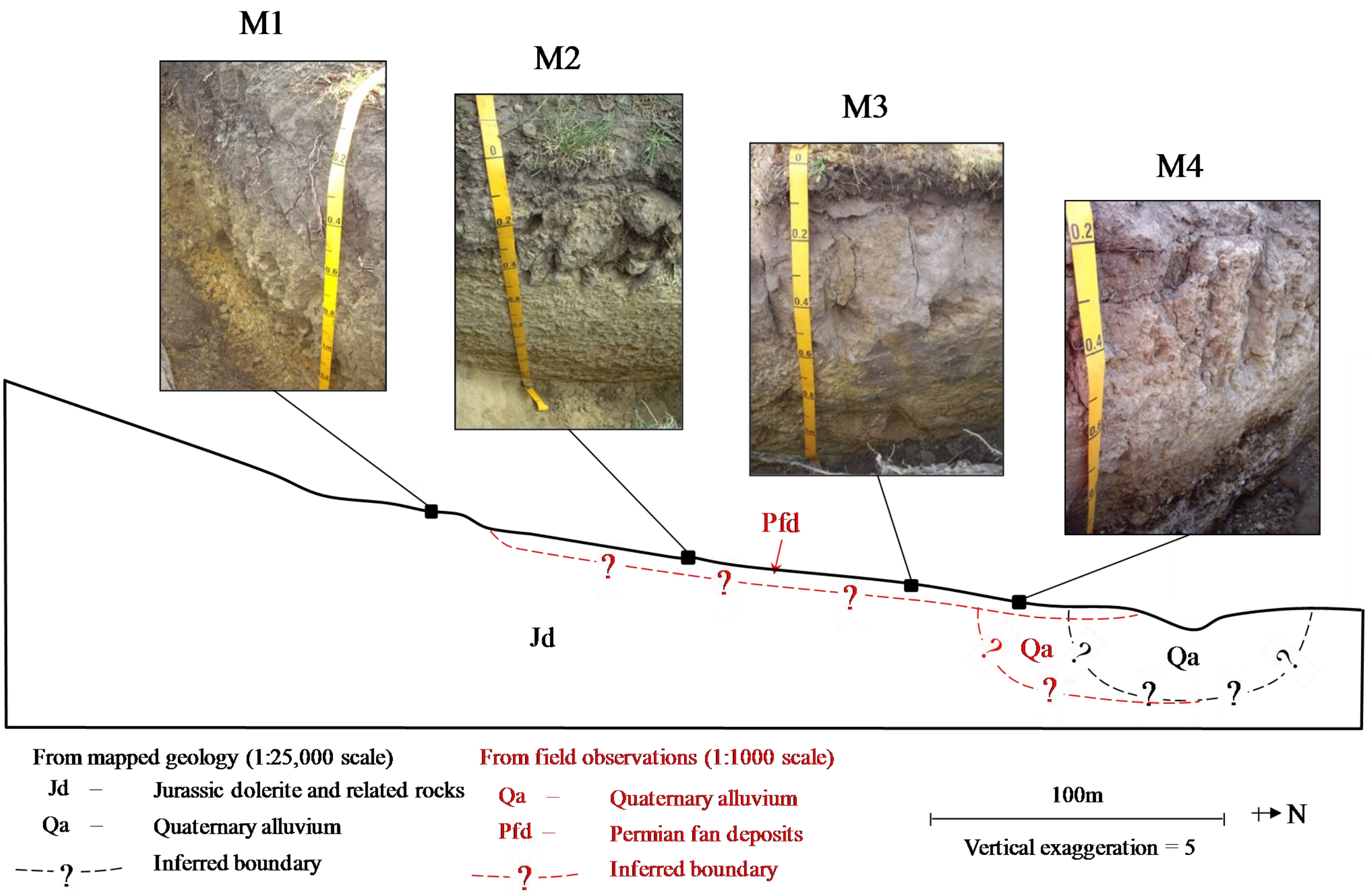

Figure 62: Landscape position and cross-sectional 1:25,000 scale geology of the catena. Black lines signify mapped geology information 1:25,000 scale whereas red lines are refinements made from field observations (approx 1:1000 scale).

Table 36: Summary of key profile features

Horizon	Depth (cm)	Matrix Colour (moist)			Texture	Structure							Consistence (moist)
						Primary				Secondary			
M1													
A11	0-8	10YR	2	1	CL	M	m	SB	+	M	m	SB	Weak
A12	8-35	2.5Y	2.5	1	LC	M	c	PR	->	M	m-c	AB	Weak
B21	35-62	2.5Y	3	2	LC	M	c	PR	->	M	m-c	AB	Firm
B22	62-93	2.5Y	4	3	LC	M	c	PR	->	M	m-c	LE	Firm
B23	93-145	2.5Y	4	4	MC	M	c	LE	+	M	m-c	LE	Firm
C	145-165+	2.5Y	4	4	SC			M					
M2													
A1p	0 – 10	10YR	3	1	SL	W	m	PO	+	W	f	PO	Weak
B21	10 – 28	2.5Y	4	2	SLC	M	c	CO	->	W	m-c	AB	Firm
B22	28 - 56	2.5Y	4	2	LC	M	c	PR	->	W	m-c	AB	Firm
BC1	56 – 74	10YR	5	5	SCL			V					Strong
BC2	74 – 102	10YR	5	4	SCL			V					Strong
BC3	102 – 132	5Y	4	4	SLC			V					Very firm
BC4	132 - 168+	10YR	5	6	SCL			V					Strong
M3													
A1p	0 – 13	10YR	3	1	SL	M	m	SB	+	M	m	SB	Weak
B21	13 – 37	10YR	3	2	SCL+	S	c-vc	CO	->	M	m	PR	Firm
B22	37 – 76	2.5Y	4	4	LC	M	c-vc	PR	->	M	m-c	PR	Very firm
BC1	76 – 93	10YR	5	6	S			V					Strong
BC2	93 – 108	10YR	5	4	SSL			V					Strong
BC3	108 - 115	5Y	4	4	SLC			V					Strong
BC4	115 - 144+	10YR	5	6	SCL			V					Strong
M4													
A11p	0-11	10YR	3	1	SL	M	m-c	PO	+	M	m	PO	Weak
A12	11-24	10YR	3	2	SL+	W	c-vc	PO	+	W	m	PO	Weak
B21	24-46	10YR	4	3	LC	S	c-vc	PR	->	M	c	AB	Firm
B22	46-69	2.5Y	4	3	LC	M	c-cv	PR	->	M	c	AB	Firm
B23	69-92	2.5Y	5	4	SL			V					Very strong
2B21b	108-132*	2.5Y	4	3	LC	M	m-c	AB	->	M	m	AB	Firm
2B22	132-156	2.5Y	4	3	LC	M	m-c	AB	->	M	m	AB	Weak
2BC1	156-183	2.5Y	5	4	SC	W	F	PO					weak
2BC2	183-199	2.5Y	6	6	SC	W	F	PO					weak

See Appendix 1 for a description of codes

*This discontinuous depth between the B23 and 2B21b indicates the thickness of stone-line

Soil analysis

The analysed soil chemistry demonstrates there are differences between the observed profiles (Figure 63 and Table 37).

Soil pH generally had an alkaline reaction trend with depth with most profiles having a pH greater than 7 (1:5 $CaCl_2$) below a depth of 75 cm. The exception to this was M2 which had a slightly acid profile (pH of approximately 6.0) and no change in pH was observed below a depth of 20 cm. All profiles had an increase in pH associated with the surface horizons which was assumed to be due to lime application during vineyard establishment. This resulted in similar soil pH values for these surface layers (pH 1:5 $CaCl_2$ of 6.4 – 6.6). Profile M1 had the lowest topsoil pH of all the profiles with a value of 5.3 (1:5 $CaCl_2$), whereas the highest pH occurred at M4 (pH 1:5 $CaCl_2$ of 8.3) below a depth of 120 cm.

Values of exchangeable Ca^{2+} and exchangeable K^+ decreased with depth at all profiles, whereas values of exchangeable Mg^{2+} and exchangeable Na^+ both generally increased with depth. While exchangeable K^+ generally decreased with depth, at profiles M1, M2 and M3 there was subsequent accumulation at specific horizons deeper within each profile. Profile M4 had highest values of exchangeable K^+ and did not show any accumulation with depth. It was assumed that the high topsoil values of exchangeable Ca^{2+} and exchangeable K^+ measured in all profiles was in part due to fertiliser and lime application. Within profiles M1 and M3 the values of exchangeable Mg^{2+} were greatest within the mid-subsoil horizons (55 - 75 cm) with values then decreasing with depth. At both M1 and M4, the values of exchangeable Na^+ peaked at 120 cm before subsequently declining in value within deeper soil layers. Exchangeable sodium percentage (ESP) indicate all profiles were sodic (ESP > 6 %) with horizons becoming strongly sodic (ESP > 15 %) in all subsoils.

The chemical data indicate that profile M1 generally has the highest fertility of the four profiles with highest values of exchangeable Mg^{2+}, ECEC and organic carbon throughout the entire profile as well as highest topsoil values of exchangeable Ca^{2+} and exchangeable

K^+. Profile M2 had the lowest fertility with distinctly lower ECEC, exchangeable Ca^{2+} and exchangeable K^+.

The coarse columnar structure at the M2, M3 and M4 profiles allowed sand to in-fill from the sandier overlying horizons. At both M2 and M3 profiles the thickness of the sand in-fill was sufficient to allow it to be sampled and analysed separately to the surrounding soil (see Table 37). In both profiles the sand had lower values of all exchangeable cations and lower ECEC than the surrounding soil.

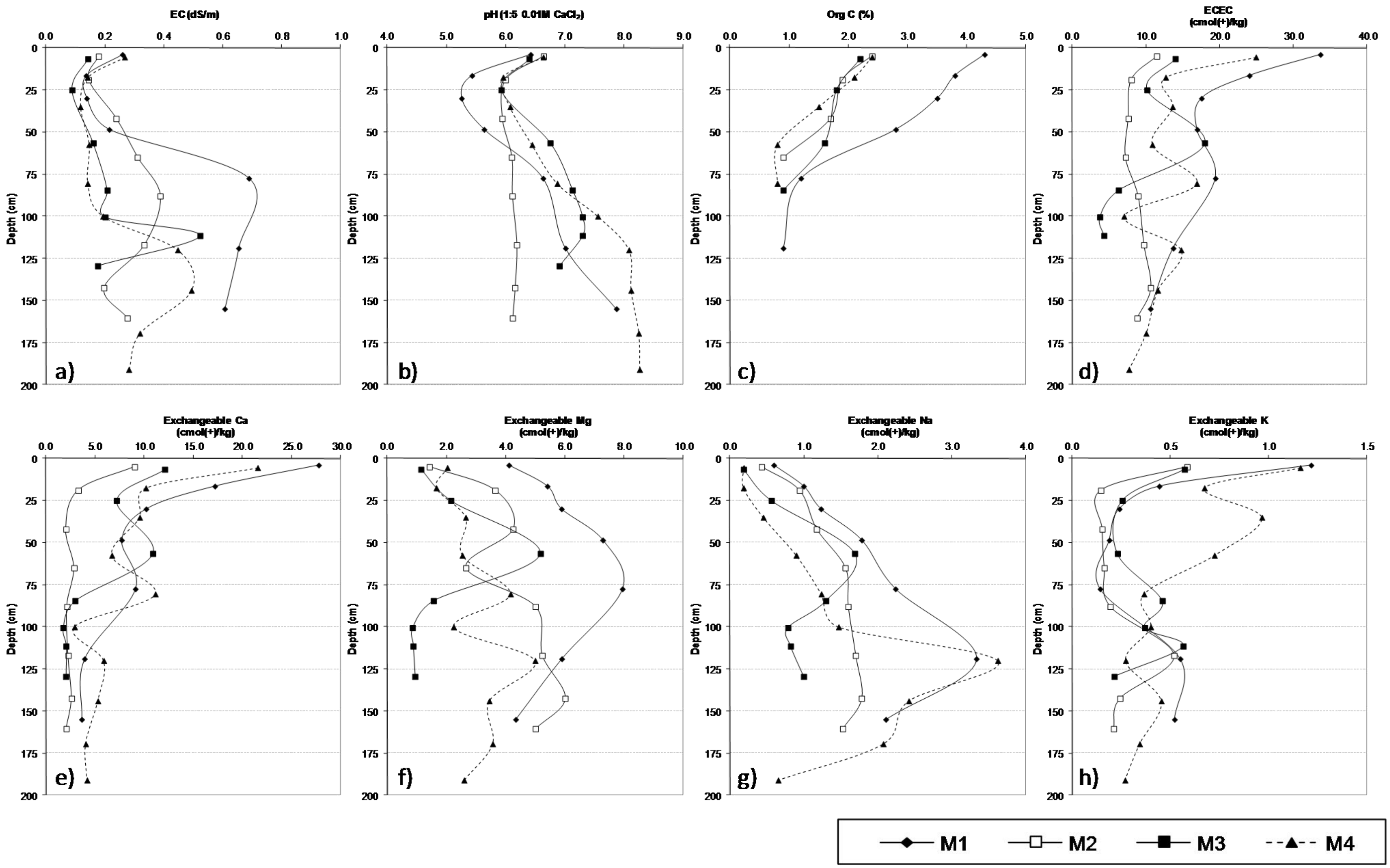

Figure 63: Combined soil chemistry of the profiles within the catena.

Table 37: Selected soil chemistry analysis.

	Horizon	Depth (cm)	pH (1:5) H_2O	pH (1:5) $CaCl_2$	EC (dS/m)	Exchangeable Cations (cmol(+)/kg) Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	ECEC	ESP (%)	Org C (%)
M1	A11p	0-8	6.8	6.4	0.26	27.7	4.1	0.6	1.2	33.7	1.8	4.3
	A12	8-35	5.8	5.3	0.14	13.7	5.6	1.1	0.3	20.8	5.4	3.7
	B21	35-62	6.1	5.6	0.21	7.7	7.3	1.8	0.2	16.9	10.5	2.8
	B22	62-93	7.6	6.6	0.69	9.1	7.9	2.2	0.1	19.4	11.5	1.2
	B23	93-145	8.0	7.0	0.65	3.9	5.9	3.3	0.6	13.7	24.3	0.9
	C	145-165	8.7	7.9	0.61	3.6	4.3	2.1	0.5	10.6	19.9	-
M2	A1	0-10	6.9	6.6	0.18	9.0	1.4	0.4	0.6	11.5	3.7	2.4
	B21	10-28	6.1	6.0	0.14	3.3	3.6	0.9	0.1	8.0	11.7	1.9
	B22	28-56	6.1	5.9	0.24	2.0	4.2	1.2	0.2	7.6	15.4	1.7
	BC1	56-74	6.5	6.1	0.31	2.9	2.7	1.6	0.2	7.2	21.5	0.9
	BC2	74-102	6.5	6.1	0.39	2.1	5.0	1.6	0.2	8.9	17.9	-
	BC3	102-132	6.6	6.2	0.33	2.3	5.2	1.7	0.5	9.7	17.5	-
	BC4	132-168	6.7	6.2	0.20	2.6	6.0	1.8	0.2	10.6	16.7	-
	B22 (sand)*	10-28	6.1	5.8	0.29	2.0	1.9	0.7	0.1	4.8	14.7	-
	B22 (sand)*	28-56	6.1	5.8	0.21	1.4	2.0	0.7	0.1	4.2	16.4	-
M3	A1p	0-13	6.7	6.4	0.14	12.1	1.1	0.2	0.6	14.0	1.3	2.2
	B21	13-37	6.0	5.9	0.09	7.2	2.1	0.6	0.3	10.1	5.5	1.8
	B22	37-76	7.2	6.8	0.16	10.9	5.2	1.7	0.2	18.0	9.4	1.6
	BC1	76-93	7.9	7.1	0.21	3.0	1.6	1.3	0.5	6.3	20.7	0.9
	BC2	93-108	8.1	7.3	0.20	1.7	0.9	0.8	0.4	3.7	21.0	-
	BC3	108-115	8.1	7.3	0.52	2.0	0.9	0.8	0.6	4.3	19.1	-
	BC4	115-144	7.9	6.9	0.18	2.0	0.9	1.0	0.2	4.2	24.0	-
	B22 (sand)*	13-37	6.1	5.7	0.09	2.3	0.7	0.3	0.2	3.5	9.1	-
M4	A11p	0-11	6.6	6.6	0.27	21.5	2.0	0.2	1.2	24.9	0.7	2.4
	A12	11-24	5.9	6.0	0.14	10.2	1.7	0.2	0.7	12.7	1.5	2.1
	B21	24-46	6.2	6.1	0.12	9.5	2.6	0.5	1.0	13.6	3.3	1.5
	B22	46-69	7.0	6.4	0.15	6.7	2.5	0.9	0.7	10.8	8.3	0.8
	B23	69-92	7.6	6.9	0.14	11.1	4.2	1.2	0.4	16.9	7.3	0.8
	stoneline	92-108	8.1	7.6	0.19	2.9	2.2	1.5	0.4	7.0	20.9	-
	2B21b	108-132	8.6	8.1	0.45	5.9	5.0	3.6	0.3	14.8	24.5	-
	2B22	132-156	8.7	8.1	0.49	5.3	3.4	2.4	0.5	11.6	20.8	-
	2BC1	156-183	8.7	8.2	0.32	4.0	3.6	2.1	0.3	10.0	20.7	-
	2BC2	183-199	8.9	8.3	0.28	4.2	2.6	0.7	0.3	7.7	8.5	-

* sand sampled from cracks

Root Distribution

Distinctly different root growth was observed between the four soil profiles. Profile M1 had substantially more roots (4483) than the other three profiles (2710, 1177 and 1942 for profiles M2, M3 and M4 respectively, Table 38) indicating total root number generally decreased down slope. The exception to this was profile M4 which had more total roots compared with profile M3 even though it was lower in the landscape. In all profiles root frequency decreased as root size increased with fine root growth (< 1 mm) being dominant. However, the percentage of distribution of the respective root sizes varied between profiles. The occurrence of fine roots was especially dominant at profile M1, comprising 91.6 % of all observations. This contrasted with 83.6 %, 85.6 % and 73.1 % at M2, M3 and M4 respectively. Profile M1 also had the lowest percent occurrence of 1 – 2 mm roots, accounting for only 5.6 % of the root observations at this profile. While M4 had the lowest percentage of fine roots, it had the highest percentage of 1 – 2 mm roots (22.3 %). No coarse roots (> 5 mm) were observed at this profile. While marked differences in total root numbers were present between profiles M2 and M3, the percentage distribution of root sizes was very similar. The percentage occurrence of fine roots (approximately 85 %) and 1 - 2 mm roots (12 %) was between the respective percentages observed at both M1 and M4 profiles.

Root distribution was also different between the four profiles. Highly diverse root distribution was observed at profile M1. This was particularly apparent in the distribution of fine roots (Figure 64a) that showed substantial root growth to 100+ cm across the entire profile face. Distinct ‘hotspots’ of root growth were observed at 80 to 100 cm. The abundance of this root size was considerably greater than the other profiles for all depths (Figure 69). While roots were observed across the entire profile face, they were mainly confined to cracks caused by the prismatic primary structure (Figure 68). The occurrence of larger root sizes (> 1mm) was generally limited to depths of 15 – 60 cm.

At profile M2, the distribution of fine roots with depth was noticeably different to the other profiles. While most occurred within the upper 60 cm of the profile (similar to other profiles), the greatest abundance of these roots occurred in the surface soil (0 – 10 cm). This was in contrast to the other profiles which had greatest root abundance between 10 – 30 cm (Figure 69). This was only apparent within the fine roots, with other root sizes having similar distribution to most other profiles.

The least root abundance occurred at profile M3 and this occurred across all root sizes (Table 38). This was reflected in Figure 69 where the number of all root sizes was lower at all profile depths. Root growth was mainly limited to the upper 40 cm, however isolated regions of fine root growth occurred between 60 – 80 cm depth (Figure 66). This was mainly observed within the fine roots and only occurred in association with subsoil cracks (Figure 68).

Profile M4 had two distinct regions of root growth. While the bulk of the root growth occurred within the upper 10 – 40 cm of the profile, considerable root growth also occurred at 100 – 120 cm depth. This was considerably different to the other profiles, particularly within the 1 – 2 mm roots (Figure 69). Substantially higher root growth of mid-sized roots (1 – 5 mm) also occurred in the upper soil layers at this profile compared to the other profiles. No coarse roots were observed within this profile.

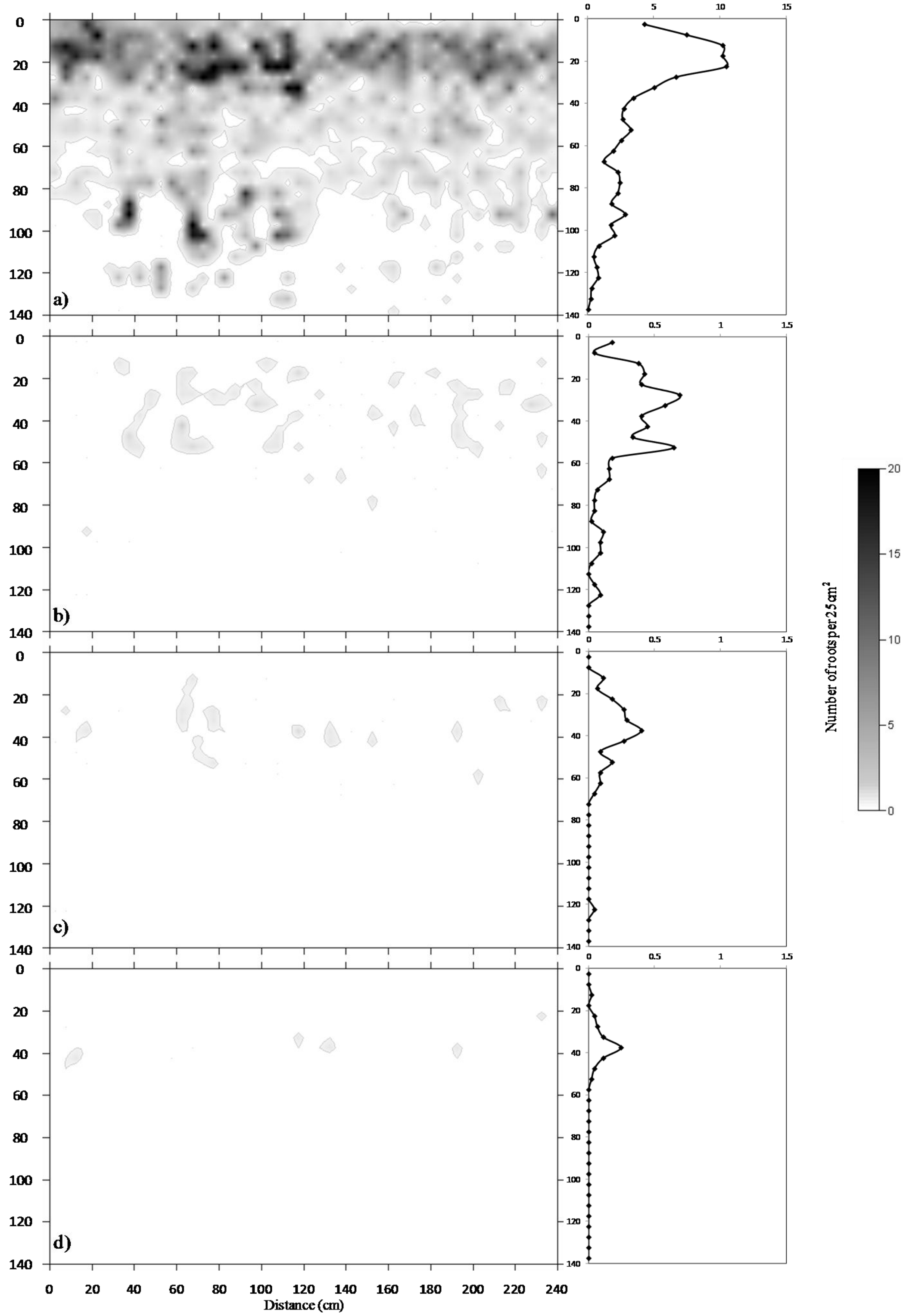

Figure 64: Root distribution for profile M1 showing the distribution of the following diameter classes: a) < 1mm; b) 1 – 2 mm; c) 2 – 5 mm; d) > 5 mm. Darker shading indicates higher root density. The right-hand graph shows the percentage of total roots for each size class with depth. Note: the scale for < 1 mm root class is ten times greater than the other classes.

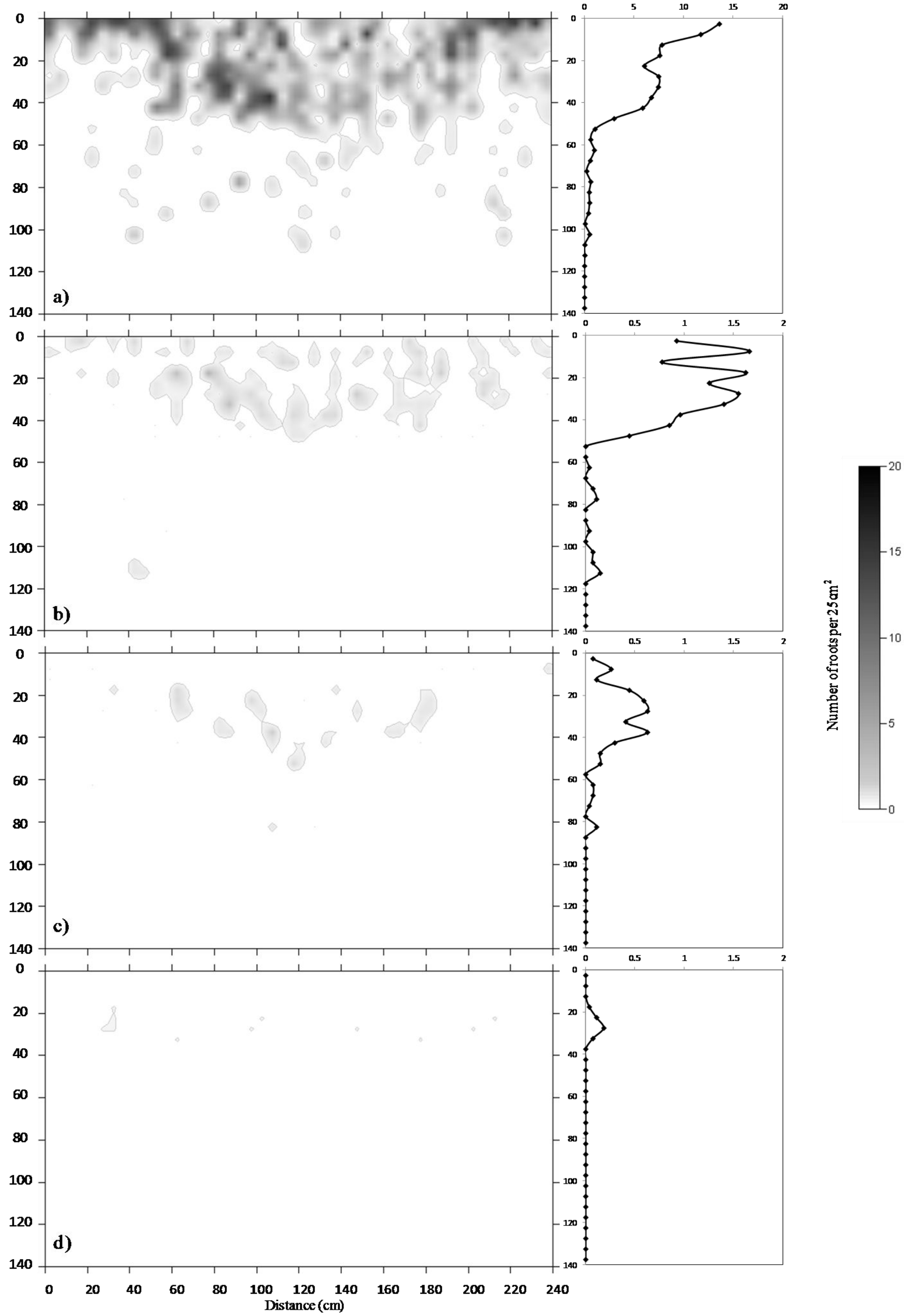

Figure 65: Root distribution for profile M2 showing the distribution of the following diameter classes: a) < 1mm; b) 1 – 2 mm; c) 2 – 5 mm; d) > 5 mm. Darker shading indicates higher root density. The right-hand graph shows the percentage of total roots for each size class with depth. Note: the scale for < 1 mm root class is ten times greater than the other classes.

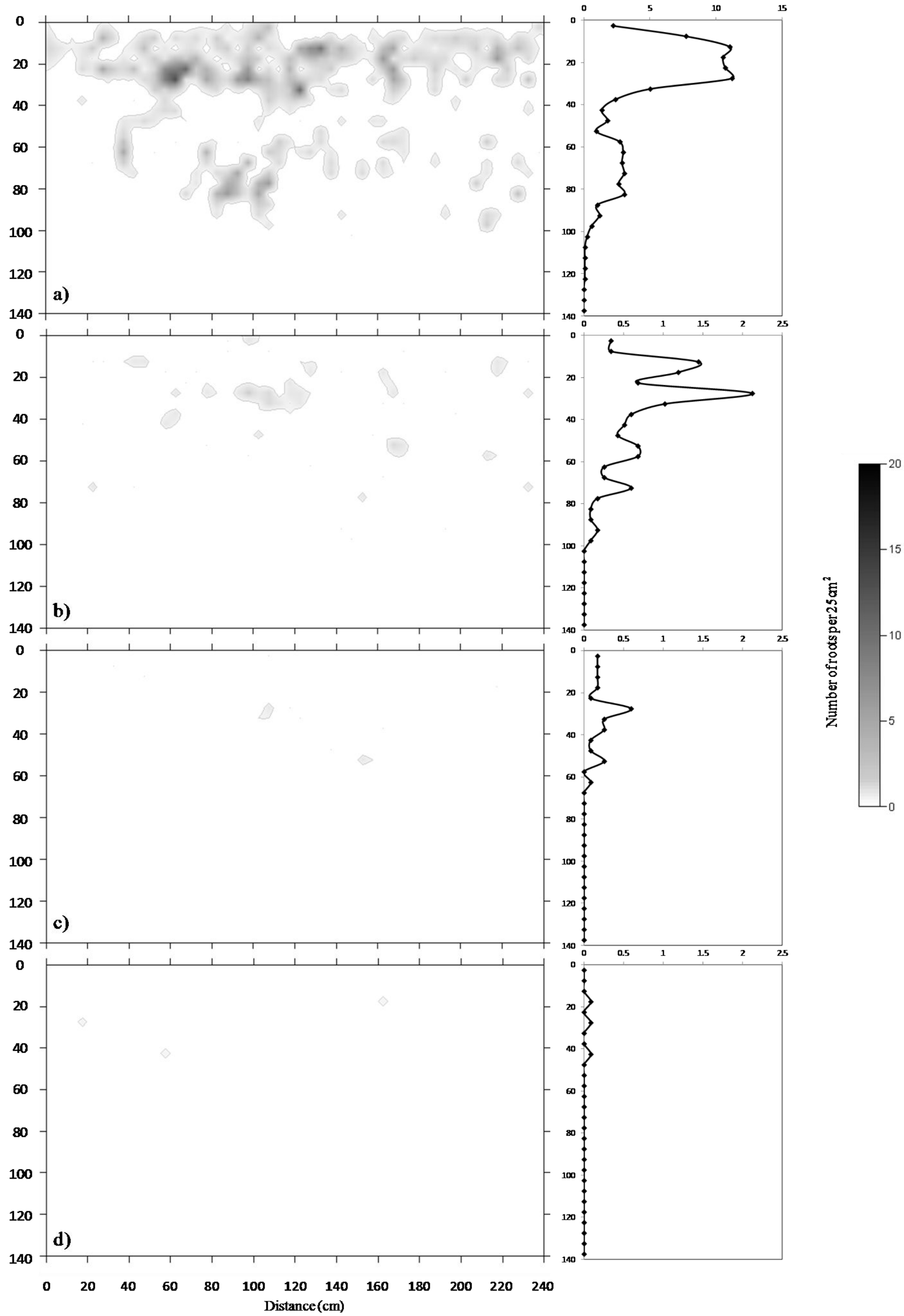

Figure 66: Root distribution for profile M3 showing the distribution of the following diameter classes: a) < 1mm; b) 1 – 2 mm; c) 2 – 5 mm; d) > 5 mm. Darker shading indicates higher root density. The right-hand graph shows the percentage of total roots for each size class with depth. Note: the scale for < 1 mm root class is six times greater than the other classes.

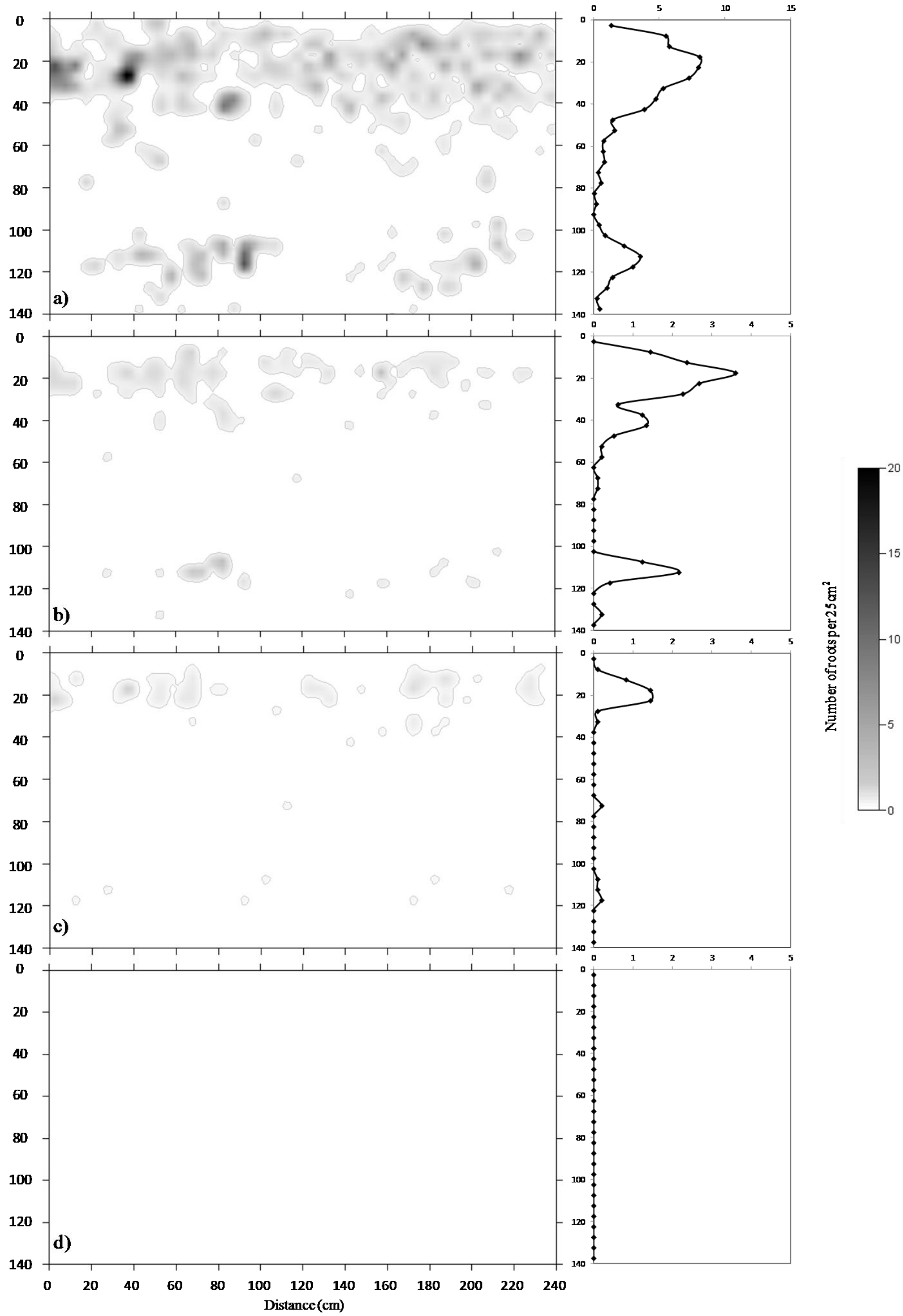

Figure 67: Root distribution for profile M4 showing the distribution of the following diameter classes: a) < 1mm; b) 1 – 2 mm; c) 2 – 5 mm; d) > 5 mm. Darker shading indicates higher root density. The right-hand graph shows the percentage of total roots for each size class with depth. Note: the scale for < 1 mm root class is three times greater than the other classes.

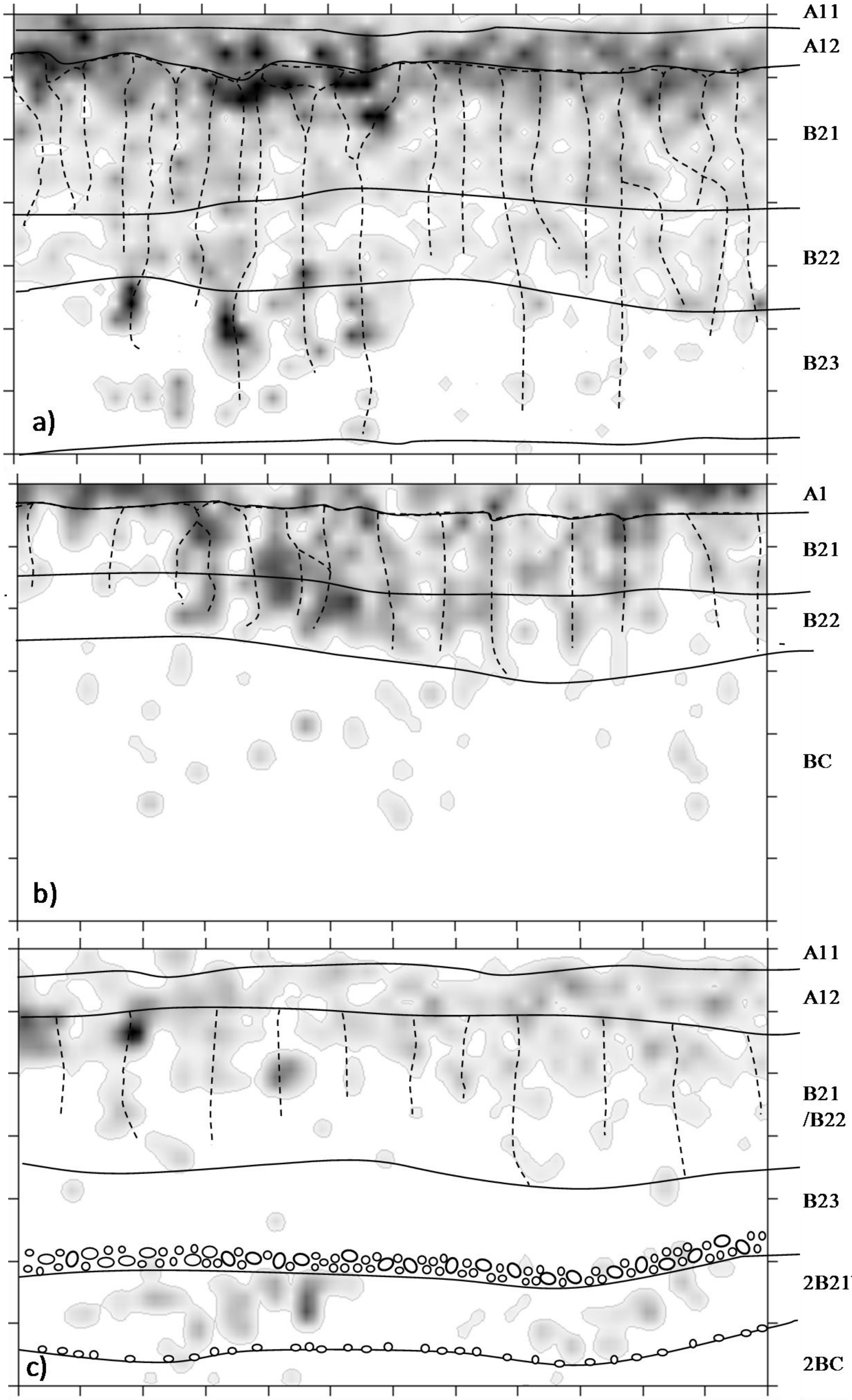

Figure 68: Fine root distribution and primary profile features. Profiles are a) M1; b) M2; and c) M4. Dashed lines indicate primary structure and solid lines indicate approximate horizon boundaries. Circles within M4 indicate presence of stonelines. Scale increment is 20 cm. Note: profile M3 not shown as similar to profile M2.

Root numbers with depth for the different root size classes

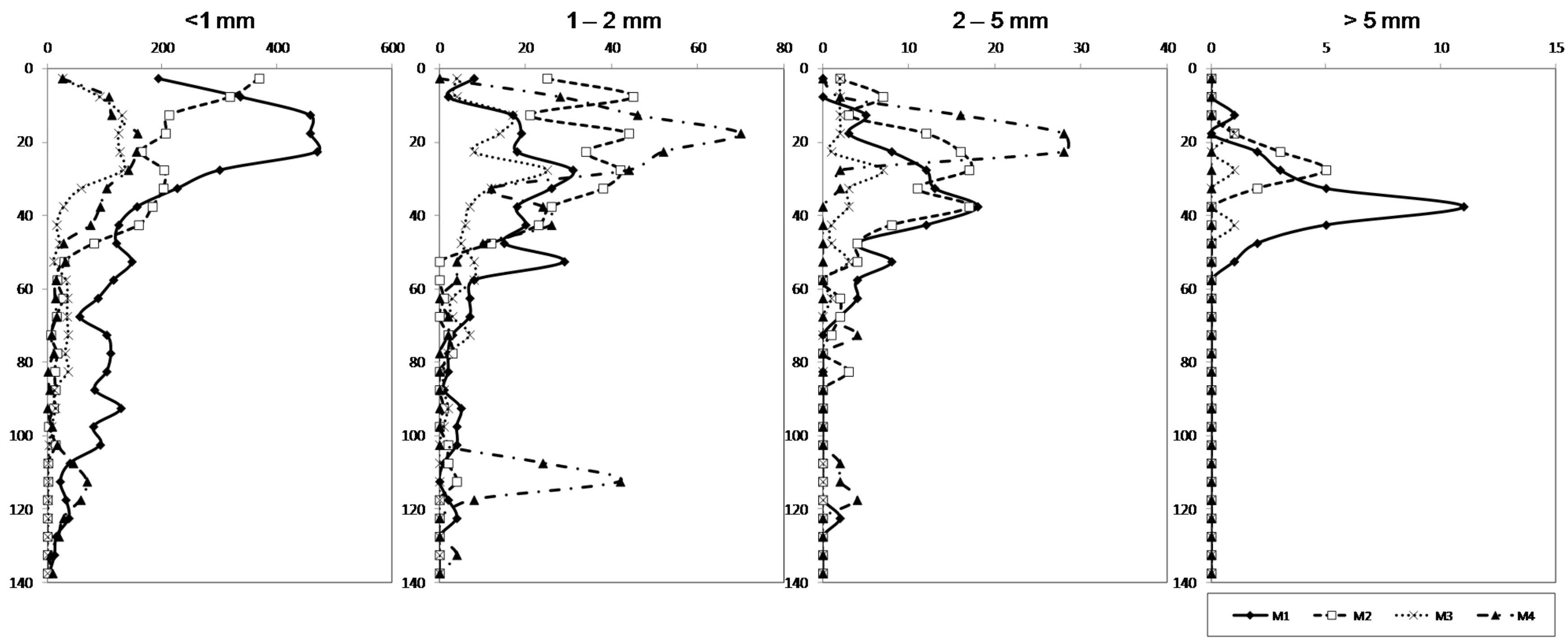

Figure 69: Root numbers with depth of the different root size classes of the catena.

Table 38: Total root numbers for the respective catena profiles. Numbers in brackets indicate the percentage of the total root observations for each profile.

	Root numbers				
	< 1mm	1-2 mm	2-5 mm	> 5mm	Total
M1	4105 (91.6)	253 (5.6)	95 (2.1)	30 (0.7)	4403 (100)
M2	2265 (83.6)	325 (12.0)	109 (4.0)	11 (0.4)	2710 (100)
M3	1008 (73.1)	138 (11.7)	28 (2.4)	3 (0.3)	1177 (100)
M4	1420 (73.1)	432 (22.3)	90 (4.6)	0 (0.0)	1942 (100)

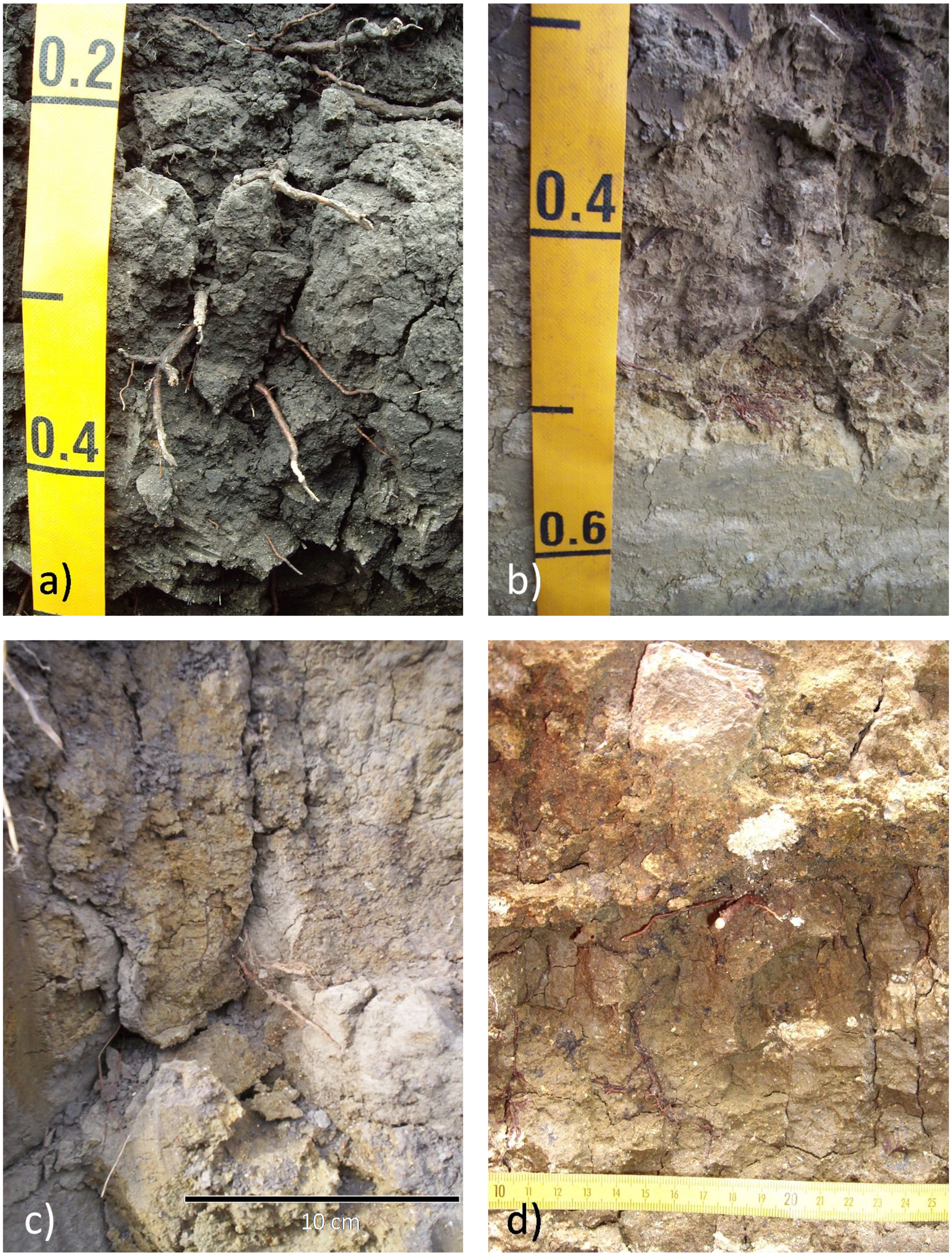

Figure 70: Examples of constrained root growth. Showing a) roots growing around prismatic structure (M1); b) roots impeded by compact sodic sandy fan deposits (M2); c) roots restricted to sandy cracks (M3); and d) roots within deep buried clay (M4).

Estimation of Plant Available Water

The estimated values of plant available water (PAW) using the upper 1 m of the soil profile indicate that the soil profiles are reasonably similar, with the range of PAW values varying by only 7 mm/m . However, when the PAW was modified to take into account the effective root zone (90% of root observations) a difference of 90 mm/m was seen (Table 39) with M2 having the lowest PAW of 54.6 mm/m compared to M4 with 146.3 mm/m.

Table 39: Estimation of plant available water (PAW)

Profile	PAW (1 m depth) (mm/m)	Depth of 90% root observations (cm)	PAW (90 % roots) (mm)
M1	130.7	87.5	115.2
M2	123.6	42.5	54.6
M3	129.7	72.5	91.9
M4	123.4	117.5	146.3

Multivariate analysis of root distribution

Two-factor loading plots describing analysis of root distribution are shown in Figure 71. These plots account for just over half of the variation in root growth observed from the different profiles (54.2 %, 56.3 %, 50.7 % and 60.0 % for profiles M1, M2, M3, and M4 respectively). Table 40 shows that most of the relationships between the measured variables were significant, however the correlations were generally weak.

For most loading plots, the occurrence of < 1 mm roots was directly opposite depth, signifying a negative relationship. This was supported with negative correlations between these factors for all profiles indicating that the numbers of fine roots decline as depth increases. Correlation coefficients of <1 mm roots and depth were stronger at both M1 and M2 profiles than at either M3 and M4 profiles (-0.56 and -0.52 compared to

-0.40 and -0.33 respectively). This was also demonstrated on the loading plots with greater distances between < 1 mm roots and depth for both M1 and M2 profiles.

Within most profiles there were also strong positive correlations between the respective root sizes. This was indicated by close clustering of the root size classes on the loading plots (Figure 23) as well as positive coefficients (Table 14). This was generally strongest between adjacent root size classes, for example the correlation coefficient between < 1 mm and 1 – 2 mm roots was stronger than the between the < 1 mm and 2- 5 mm roots. Profile M2 generally had stronger correlations between the root size classes than the other profiles. This was highlighted with a correlation coefficient of 0.63 between the < 1 mm roots and 1 – 2 mm roots compared to 0.24, 0.47 and 0.44 for profiles M1, M3 and M4 respectively. M1 generally had the weakest correlations between root sizes than the other profiles, reflecting the more diverse root distribution of this profile. The exception to this was between the larger root sizes (2 – 5 mm and > 5 mm) where correlation coefficient was substantially stronger (0.43 compared with 0.21 at M2 and 0.10 at M3).

Table 40: Soil Catena pairwise correlations between respective root size classes and soil position.

Indices		Correlation coefficient			
		M1	M2	M3	M4
< 1 mm	Distance	-0.0542*	-0.0429^{n}	-0.0135^{n}	-0.0654
< 1 mm	Depth	-0.5626	-0.5241	-0.3983	-0.3270
1-2 mm	Distance	-0.0340^{n}	-0.0282^{n}	-0.0066^{n}	-0.0813
1-2 mm	Depth	-0.2624	-0.3830	-0.2243	-0.2558
1-2 mm	< 1 mm	0.2418	0.6287	0.4771	0.4411
2-5 mm	Distance	-0.0039^{n}	-0.0135^{n}	0.0423^{n}	-0.0325^{n}
2-5 mm	Depth	-0.1786	-0.2140	-0.1380	-0.1873
2-5 mm	< 1 mm	0.1639	0.3859	0.2498	0.2703
2-5 mm	1-2 mm	0.3258	0.4214	0.4492	0.4639
> 5 mm	Distance	0.0529^{n}	-0.0203^{n}	-0.0251^{n}	-
> 5 mm	Depth	-0.1104	-0.0987	-0.0478^{n}	-
> 5 mm	< 1 mm	0.0623*	0.1009	0.0823*	-
> 5 mm	1-2 mm	0.1325	0.1970	0.1487	-
> 5 mm	2-5 mm	0.4274	0.2089	0.0967	-

All values are significant (P<0.001) except were indicated with ‘n’ or ‘*’ which refer to no significance and P<0.05 respectively. No > 5 mm roots were observed at M4. Note: penetration resistance was not measured at these profiles.

Depth = vertical depth from soil surface

Distance = horizontal distance from vine trunk

< 1 mm, 1-2 mm, 2-5 mm & > 5 mm = respective root size classes

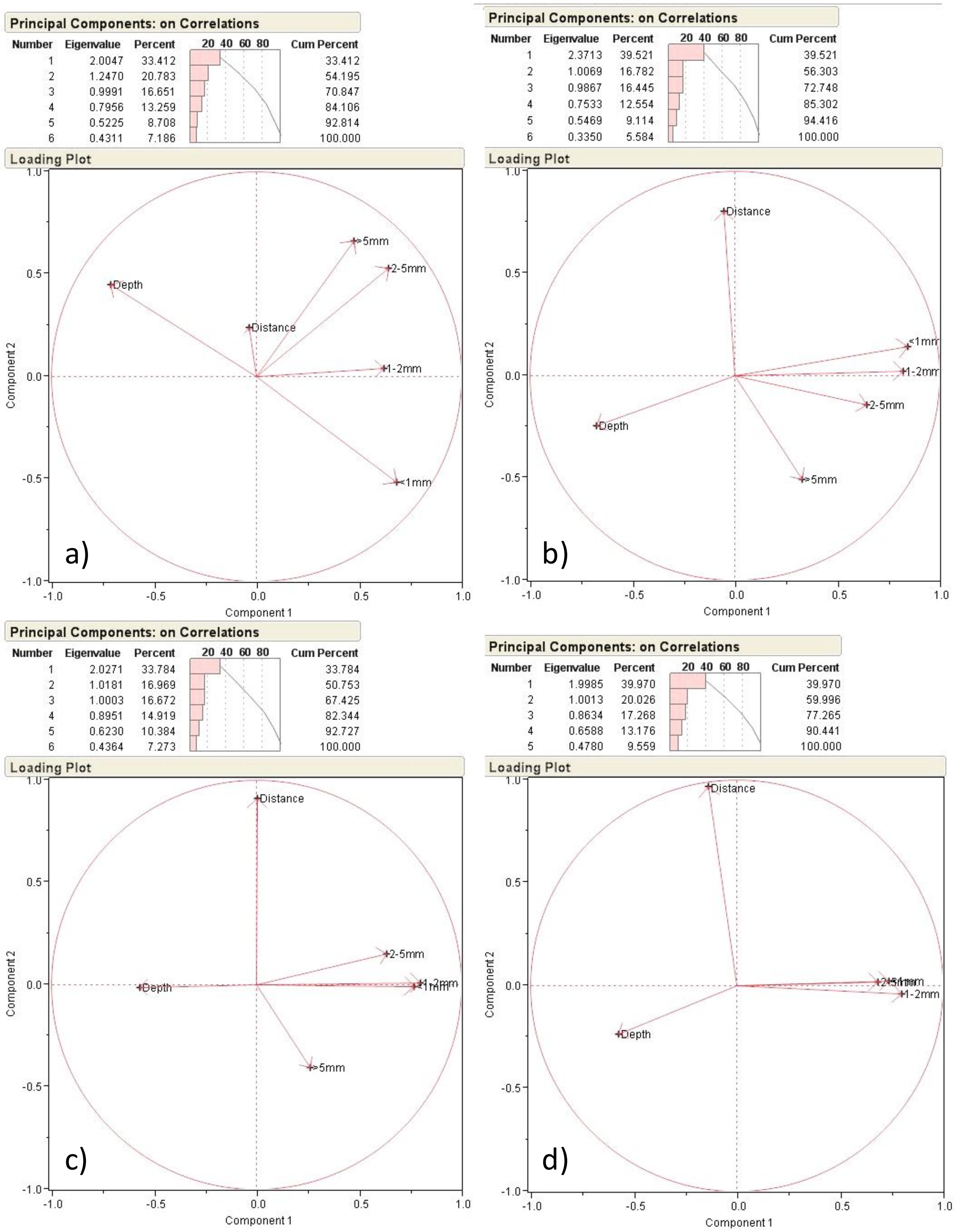

Figure 71: Two-factor loading plots of root size class and soil position,

Soil profiles are a) M1; b) M2; c) M3; and d) M4. No > 5mm roots were observed at M4. Note: no penetration resistance was measured at these profiles.

Vine measurements

The pruning weight was relatively consistent between the upper three profiles each season with only the very lower slope position (profile M4) with significantly higher pruning weight. Yield was constantly highest at both the uppermost and lowest positions (M1 and M4 respectively). Both M1 and M4 had significantly higher yields ($P < 0.05$) than either M2 or M3 with M3 having significantly lower yield than the other profiles. This was caused through differences in bunch weight as no differences in bunch number were observed between profiles in any year. Profiles M1 and M4 had statistically similar bunch weights and were significantly higher ($P < 0.05$) than the other two profiles. Bunch weight was significantly lowest at profile M2 in all years.

Pruning weight was significantly higher ($P < 0.05$) at M4 than at the other profiles in all years. This was through significantly higher ($P < 0.05$) cane weight (all years) and significantly greater ($P < 0.05$) shoot number in 2007 and 2008. Pruning weight between the other three profiles was generally similar each year except for significantly lower weight at M1 in 2008. This is also reflected in the respective cane weight for these profiles.

The significantly higher pruning weight of M4 resulted in significantly lower yield to pruning weight ratio (Y:PW) at this profile. While M1 had similar high yields to M4, the lower pruning weight led to this profile having the significantly highest Y:PW. No significant difference was observed in Y:PW between M2 and M3, however both profiles had significantly lower Y:PW than M1 and significantly higher Y:PW than M4.

Table 41: Vine measurement data from soil catena site. Different letters indicate parameter values are significantly different ($P < 0.05$) between profiles in that year.

Parameter	Year	M1	M2	M3	M4
Av. Yield:Pruning weight ratio	2006	-	-	-	-
	2007	4.05 a	2.42 b	2.30 b	1.80 c
	2008	5.04 a	2.98 b	3.13 b	1.99 c
Av. Yield (kg/vine)	2006	-	-	-	-
	2007	5.22 a	2.40 d	3.20 c	4.89 b
	2008	5.72 a	3.76 c	4.37 b	5.50 a
Av. Bunch Number (bunches/vine)	2006	-	-	-	-
	2007	41.67 a	39.46 a	40.10 a	39.54 a
	2008	44.17 a	40.00 a	41.50 a	41.83 a
Av. Bunch weight (g)	2006	-	-	-	-
	2007	116.6 a	60.8 c	79.8 b	123.8 a
	2008	128.9 a	94.0 c	105.3 b	134.5 a
Av. Pruning weight (kg/vine)	2006	2.01 b	1.93 b	2.08 b	2.62 a
	2007	1.29 b	1.33 b	1.34 b	2.72 a
	2008	1.13 c	1.47 b	1.60 b	2.76 a
Av. Shoot number (shoots/vine)	2006	27.42 a	26.42 a	27.92 a	25.92 a
	2007	20.50 b	19.76 b	20.75 b	24.50 a
	2008	20.83 b	20.50 b	20.83 b	22.50 a
Av. Cane weight (g)	2006	73.3 b	73.1 b	74.5 b	101.1 a
	2007	62.8 b	67.1 b	64.6 b	110.9 a
	2008	54.3 c	71.7 b	76.8 b	124.7 a

Discussion

Influence of parent material on soil properties

The profile with the greatest dolerite influence was M1 with the profile formed almost entirely from dolerite or dolerite derived colluvium. The upper horizons were most likely slope deposits formed from dolerite colluvium, whereas the lower part of the profile most likely developed from in-situ weathering of the underlying dolerite rock. Osok and Doyle (2004) demonstrated that many dolerite derived soils in Tasmania are highly stratified and upper horizons have a slope wash and/or aeolian component to them, with only the 'mealy' subsoil considered to be formed *in situ*. All subsoil horizons (B21 to B23) had dispersed dolerite coarse fragments throughout. These were absent in the topsoil horizons (A11p and A12) suggesting that these may represent two separate layers. The occurrence of increased sand content within the topsoil at M1 supports this idea and suggests that the upper horizons may also have foreign slope wash or aeolian components within them as shown by both Osok and Doyle (2004) and Loveday (1965). As the sand fractions were dispersed throughout the A1 horizons, it is likely that any sandy deposit took place prior to the downslope movement of the colluvium, allowing it to be incorporated and mixed through this horizon.

The strong influence of the dolerite has provided this soil profile with high clay contents and high levels of organic carbon. It also imparted a high cation exchange capacity throughout most of the profile with exchange sites dominated by exchangeable calcium and magnesium. These characteristics are similar to other Black Vertosols formed from dolerite (Osok and Doyle, 2004; Spandswick and Kidd, 2000; Tiller, 1962; Nicolls, 1958).

The other profiles had a lesser degree of doleritic influence. Both M2 and M3 profiles had lower organic carbon levels and lower ECEC (mainly through lower magnesium) than profile M1. It was concluded that only the upper subsoil horizons from both of these profiles (M2 & M3) were formed from dolerite colluvium, with the underlying material deposited from the surrounding Permian interbedded siltstone and sandstone hillslopes (S.

Forsyth, pers. comms.). The presence of both sandstone and siltstone coarse fragments within this part of the profile supports this interpretation and suggests the past soil mapping is incorrect. The sandy topsoils of both profiles were either aeolian in origin or slope wash from the surrounding hills from of sandstone and siltstones. Regardless of the origin, it is likely that the sand was similar to the sandy fraction in the topsoil of M1. Both the lower ECEC and the sandy texture help explain the lower nutrient status within the topsoils of profiles M2 and M3.

While both M2, M3 and M4 profiles seem to have similar type of soil parent material and subsequent soil development, there were stark differences in soil chemistry. M2 had distinctly lower pH within the subsoil as well as lower ECEC, exchangeable Ca^{2+} and exchangeable K^{+} throughout the profile when compared to M3. In contrast exchangeable Mg^{2+} was higher within M2, particularly in the subsoil. This suggests that the two profiles have either formed over different timeframes (M2 being more leached and therefore older) or formed at the same time but from variable slope materials (different mineralogy or texture).

While the topsoil of profile M4 had a similar colour and texture to both M2 and M3, the subsoil was highly stratified with many distinct layers of diversely textured materials. This was reflected within the soil chemistry with values of ECEC and exchangeable cations fluctuating with depth, indicating deposition of various materials have been responsible for the formation of this soil. The increase in exchangeable Na^{+} between 108 – 132 cm depth corresponded to a higher clay content and ECEC at this part of the profile, enabling greater retention of cations. This is reflected with an increase in exchangeable Mg^{2+} at this depth also. It was concluded that profiles M2, M3 and M4 had similar colluvial material in the upper horizons however profile M4 differed as this colluvium overlay alluvial sub-layers.

All profiles demonstrate an increase of exchangeable Na^{+} with depth and subsequent accumulation in lower horizons. As previously discussed in Chapter 6, the accumulation of exchangeable Na^{+} was associated with the high Na^{+} content of the rainfall in eastern

Tasmania (Jackson, 2000). Therefore Na^+ is regularly supplied to the landscape where it can be subsequently leached through the soil profile. The accumulation of exchangeable Na^+ resulted in all profiles being classed as sodic (Isbell, 1996) with subsoil horizons containing an exchangeable sodium percentage (ESP) of greater than 6 %. The subsoils of all profiles were strongly sodic (ESP > 15 %) reflecting the accumulation of exchangeable Na^+ with depth. These high ESP values typically aid in the development of coarse columnar structure common to profiles M2, M3 and M4 profiles. It was also assumed to be the reason these horizons had very strong strength at low moisture contents. While penetration resistance was not directly measured within these profiles, the field descriptions of consistence (Table 8) indicate that the sodic horizons did have high strength. The sand contained within the structural cracks also had high ESP values (9 – 15 %) and this caused hard setting in the sand and the formation of sand skins/cutans.

All profiles had the highest exchangeable Ca^{2+} and exchangeable K^+ within the surface horizons. While it was assumed that much of this was due to fertiliser and lime application, the respective profiles had differing values of these cations due to differences in ECEC. This demonstrates that different soil parent materials will affect the response to land management inputs.

Each profile had an increase in electrical conductivity (EC) within subsoil horizons. At both M3 and M4 this occurred in a distinct increase at approximately 100 cm depth. EC values decline at greater depths indicating a spike or bulge at these depths. A similar trend occurs at M2 although the bulge is less pronounced and occurs at a shallower depth. At M1, the increase in EC is dramatic with distinctly higher EC values from the B22 downwards. Causes of the changes in EC appear to be different for each profile.

Influence of soil properties on root distribution

In all soil profiles, root growth showed a strong relationship to the primary structure of the profiles. This is because the bulk of the roots were restricted to within the major cracks of the coarse hard structural units. At M2, M3 and M4 profiles the subsoil structure was very coarse (> 200 mm) and roots were mainly constrained to sand filled cracks surrounding the columns. This was similar to root growth distribution recorded at both the Kurosol-Burnt and Kurosol-Scalped profiles discussed in Chapter 4. Within the M1 profile, roots were also mainly contained within structural cracks, however the primary structure was finer (50 – 100 mm) and parted more readily resulting in more root growth within the primary structural units than the other profiles. The degree to which the soil structure constrained root growth was also demonstrated in the correlation coefficients between the respective root sizes. For root sizes less than 5 mm, the weakest coefficients occurred within the M1 profile signifying the more diverse root distribution. In contrast, the other profiles had relatively strong correlations between root sizes indicating that roots were more likely to be located together, with correlations strongest at profile M2 demonstrating a greater constraint to root growth within this profile. However, correlations between > 5 mm roots and 2 – 5 mm roots were stronger at M1 compared to M2 and M3 respectively. This was most likely due to the increased number of > 5mm roots at the M1 profile.

Root abundance reflected the differences in soil structure with substantially more roots throughout the M1 profile (4403 total roots) compared to 2710, 1177 and 1942 total roots at M2, M3 and M4 profiles respectively. Differences in root numbers were mainly due to the occurrence of fine roots (< 1 mm) with M1 also having a higher proportion these roots compared to the other profiles. Both Wang *et al* (2001) and Zhang and Bravdo (2001) found an increase in fine root production associated with restricted soil volumes. Therefore, while high numbers of roots were observed within the M1 soil profile, it is considered that the vertic soil structure restricted root distribution more than the correlation coefficients between root sizes for this profile would suggest.

The majority of root growth occurred within the upper 40 cm of all soil profiles with root numbers generally declining with depth. Soil chemistry generally reflected this trend, in which ECEC, organic carbon, exchangeable Ca^{2+} and exchangeable K^{+} were also highest within the topsoil and then declined with depth. Soil pH, exchangeable Na^{+} and ESP all increased with depth demonstrating an inverse relationship with root number. The high ESP of all soil profiles influenced root growth due to the development of coarse or massive structure which restricted root elongation. In the subsoils, root growth was mainly restricted to within sandy cracks that occurred in between structural units.

While root growth was highest within the upper horizons, most profiles did not have highest root abundance occurring in the region of highest fertility. While the upper 0 – 10 cm of all profiles was considered the most fertile, highest root abundance generally occurred between 10 – 35 cm. This was consistent with the recorded root distribution within all profiles discussed in previous chapters. Similar to these chapters, the reduced root growth near to the surface was assumed to be through increased soil temperature and decreased soil moisture due to increased evaporation. The noticeable exception to this pattern of root distribution was at profile M2 which had the highest root growth at 0 – 10 cm depth. This was the only profile to display such a distribution of root growth throughout the entire study. The depth of root growth was also restricted within this profile with almost all roots occurring in the upper 40 cm. However, while the depth of root growth was limited to above 40 cm depth, the abundance of roots was high with the second highest root frequency of the catena occurring at this profile. This occurred across all root sizes (Table 13) and suggested that the restriction within the subsoil at M2 has resulted in enhanced root growth within the upper horizons. This is in contrast to Van Huyssten (1986) who noted that compensatory root growth did not occur in grapevines and that root growth in the topsoil was not improved when a limitation on growth was imposed on the subsoil. Kirchhof *et al* (1991) also concluded that an increase in root growth can only be achieved by increasing the favourable rooting environment rather than constricting growth elsewhere. Consequently the increased root growth within the upper horizons of the M2 profile was attributed to favourable condition(s) rather than the hostile nature of the subsoil. However, it is noted that profile

M2 had the lowest ECEC, exchangeable Ca^{2+} and exchangeable K^{+} of the studied profiles as well as the shallowest depth to any sodic horizon (ESP > 6 %) with all horizons below 10 cm depth being sodic and all horizons were strongly sodic (ESP > 15 %) at depths below 28 cm. Consequently the M2 profile was considered to have the lowest fertility and the most hostile soil chemistry such that this profile had the least favourable conditions for root growth of all the profiles within the catena. Therefore it was concluded that the increase in root growth in the 0 – 10 cm of this profile was not caused through more favourable soil chemistry or through constriction of root growth within the subsoil. The EM38 survey demonstrates that the M2 profile was located within a region of higher surface apparent conductivity (ECa) than the other profiles (Figure 56a). As the actual soil EC and depth to clay horizons was similar to other profiles, the higher ECa was assumed to be caused by increased soil moisture and consequently the likely cause of the increased root growth within the 0 – 10 cm of this profile. Profile M1 also had high ECa in the surface layers, however the values were lower than at M2. This was reflected in M1 having the second highest root numbers within the surface soil layers (0 – 10 cm). In contrast, both M3 and M4 had low ECa and both had similarly low surface root growth. This suggests that the root growth within the upper 0 -10 cm of the profiles was highly influenced by soil moisture. This is supported by Lakso (2003) and Conradie (2002) who both demonstrated root growth and distribution was mostly affected by soil moisture.

The EM38 survey also demonstrated that profile M4 had high ECa at depth compared to both M2 and M3 profiles (Figure 56b). This corresponded to a change in soil materials, with a distinct band of clay band occurring at depth (108 – 132 cm). Values of exchangeable Mg^{2+}, exchangeable Na^{+} and ECEC were higher within the clay than the adjacent horizons and at the time of examination the clay also had greater soil moisture. The increased clay content, exchangeable Na^{+} and soil moisture all influenced the EM38 response. Considerable root growth was also observed within this clay at depths between 100 – 120 cm. It was assumed that the increased root growth was due to the higher moisture content of this horizon coupled with increased exchangeable Mg^{2+}. The increased root growth at this part of the profile accounted for most of the difference in total root number observed between M3 and M4 profiles. As this horizon had the highest value of exchangeable Na^+ of all the profiles but still had substantial root growth, it can be concluded that vine roots are not inhibited by exchangeable Na^+ values of 3.6 cmol(+)/kg.

Profile M1 had high ECa throughout the profile. Much of this response was attributed to the high clay content of this soil, however it was assumed that part of the response would also be caused by increased soil moisture levels. Coupled with the high fertility, this explains the high root numbers observed at this profile. The abundant presence of vertical cracking allowed many pathways for the roots to access soil deep within the profile. The 'hotspots' of root growth at 90 – 120 cm within this profile (Figure 64a) corresponded to an increase in both exchangeable K^+ and exchangeable Na^+. The accumulation of these cations at this depth demonstrates the limit of water movement through the profile and suggests water flow is impeded below this depth. Roots at this depth therefore not only have access to increased nutrients, but potentially also have access to higher soil moisture.

A similar relationship was observed at profile M3 where an increase in root growth within the lower portion of the B22 (60 – 80 cm) was associated with an accumulation of exchangeable Na^+, exchangeable Mg^{2+} and exchangeable Ca^{2+} within that horizon. It is assumed that these cations have accumulated due to impeded water movement into the underlying fan deposit due to its massive structure related to high ESP values (> 20 %). While this profile also has a subsequent increase in exchangeable K^+ (and EC) below 100 cm depth there was no associated increase in root growth. It was believed that roots were prevented from accessing this exchangeable K^+ as they were unable to penetrate through the compact and massive subsoil.

Influence of root distribution and root function on vine growth

At this site the measured vine vigour did not relate to the infra-red image of plant cell density (PCD). While profile M4 had significantly higher pruning weight than the other profiles, the PCD image suggests that the vine vigour was only slightly greater than at profiles M1 and M3. Conversely, profile M2 had statistically similar pruning weights as M1 and M3 but was the only profile to be located in an area of moderate PCD. Differences may have resulted from the PCD image being taken one year later than the last of the on-ground measurements. However, the measurements of vine vigour showed a relatively consistent relationship between the profiles for each of the three years measured and thus it was expected that these relative differences would have been confirmed in the PCD image. This expectation was supported by other research which has demonstrated that the spatial distribution of vine vigour variation remains relatively constant over time (Bramley, 2004; Hall et al., 2002; Proffitt *et al*, 2006). The vigorous canopy growth of profile M4 in particular may have also been a contributing factor to this difference. Johnson *et al* (2003) demonstrated that vigour indices may become saturated once canopy density increases beyond a certain point. Therefore the excessive vigour at profile M4 may not have transferred to increased PCD values. The differences could also be through the PCD based on the exposure of the leaves, whereas the on-ground measurement was based on the weight of the woody growth.

The PCD values at this transect were higher compared to those measured from the vines growing on the basalt parent material (Chapter 5), even though the vines were similar age, variety, clone and had similar pruning weights across most of the profiles. The difference in PCD values was assumed to be through differing trellis systems between transects, with vines pruned on a Scott-Henry trellis (Chapter 5) having lower PCD values than those with a VSP trellis. This indicates that the PCD values from different trellis systems need to be evaluated separately which is consistent with the findings of Wells (2011).

Across the catena, differences in vine vigour were only associated with the colluvium-over-alluvial soil (M4) with all other soils along the catena having similar, but significantly lower, vine vigour. This indicates differences in soil chemistry and root distribution did little to influence vine vigour. While pruning weight was not significantly different between the upper three profiles (M1, M2 & M3), total root number varied considerably. Profile M1 had substantially more roots and had between two and four times the root abundance of the other profiles. Despite differences in root numbers, all of the measured vines generally had average cane weights greater than 60 grams per cane indicating they had moderate to high vigour (Smart and Robinson, 1991). Vines at M4 were considered overly vigorous and they consistently had average cane weights greater than 100 grams per cane. The vigour at this profile was also significantly greater than the other three profiles in all years showing that the high vigour was constant over time. Consequently, to achieve similar vigour and cane weight the different root systems had to have different efficiency of nutrient supply, with the roots at the M1 profile being less effective than the other profiles. As the M4 profile had similar root number to M2 but significantly higher pruning weights than all other profiles, its root system was therefore most efficient at nutrient and water uptake. These differences indicate that the function and efficiency of roots is more important to vine growth than total root numbers. This is similar to the studies by Richards (1983) and Cass (2004) and the findings of the Pinot Noir growth discussed in previous chapter.

Total root numbers was also not related to vine yield. Profile M1 had the highest root number and the highest fruit yield whereas M3 had the lowest root number and the lowest fruit yield. Differences in yield were due to discrepancies in bunch weight indicating soil moisture availability was likely to be different between the profiles. Moisture stress has been demonstrated to reduce bunch weight through a reduction in pericarp volume limiting berry size (Ojeda, 2001), as well as decreasing the number of berries per bunch (Kliewer *et al*, 1983; Matthews and Anderson, 1989). Therefore it is postulated that the greater number of roots within profile M1 and the access to deep buried horizons at profile M4 has allowed increased access to soil moisture than at either M2 or M3 profiles. However the increased yield at the M4 profile did not occur through high root number suggesting that supply of soil moisture within this profile is greater than the other profiles. This greater supply of moisture also explains increased vigour of the vine at this profile (Peterlunger *et al*, 2005; Van Leeuwen et. al., 2006). The excessive canopy vigour at profile M4 was likely to have reduced the fruitfulness of the vines due to decreased air movement and light exposure (Dry, 2000; Smart and Robinson, 1991).

The greater soil moisture at the M1 profile did not result in excessive vine vigour even though this profile has high fertility. This suggested that there was less uptake of moisture and nutrients by the vine roots at this site. As the root system at this profile had greater dominance of fine roots (< 1 mm) it was postulated that root turnover was also higher as fine roots generally have a shorter lifespan compared to coarse roots (Anderson *et al*, 2003). Consequently it was assumed that these vines are repeatedly assigning energy into root growth at the cost of above ground growth. The reactive and vertic nature of the clay may also have increased the turnover of roots by compressing roots when soil moisture was high. This pressure can potentially damage the structural integrity of the roots and either reduce its ability to uptake nutrients or ultimately result in root death. Within the M1 profile, the lenticular structure and presence of slickensides of the B23 highlights that this horizon undergoes repeated shrink-swell cycles. This part of the profile also had isolated areas of high fine root density.

Uptake of nutrients was also likely to have been restricted within the M2 and M3 profiles due to the sodic nature of the subsoils creating unstable and massive soil structure which confined roots to the sandy cracks. The sand had less nutrients (Table 37) so roots were not only physically confined, but also were growing through less fertile soil material. Both of these factors result in a reduction of nutrient uptake from this part of the profile. Increased root growth occurred at M3 where the surrounding soil fertility increased. This indicates that while roots were mainly constrained to the sandy cracks, there was still some access to nutrients within the soil matrix. At profile M4, a similar constriction to root growth occurred in the upper subsoil, however root access to nutrients and moisture at depth meant that limitation of nutrient and moisture supply was not evident at this profile. Therefore it was postulated that this supply of nutrients and moisture from deeper in the profile resulted in less requirement for vines to expend energy to intercept nutrients or moisture from most of the profile, meaning a smaller root system was needed to support above ground growth.

Efficiency of nutrient uptake by roots decreases when the moisture content of the soil is low (Schreiner and Scagel, 2006; Sipiora, 2005). This is particularly important when nutrient movement through the soil is mainly by diffusion (Tinker and Nye, 2000). Therefore as the soil dries, vines are likely to become increasingly deficient in nutrients such as potassium and phosphorus at all profiles except for M4. The vertic properties of the M1 profile exacerbates soil drying so it is postulated that nutrient uptake is further reduced. The effect of this would be greater in drier years and may explain why pruning weights at M1 were significantly lower than M2 in 2008. Conversely, in wetter years, or through increased irrigation, there is the increased nutrient uptake may potentially cause these vines to be overvigorous.

Vines also use nutrients stored in the roots and trunk for new vegetative growth (Obbink *et al*, 1973; Conradie, 1980) and there is suggestion that the ability of vines to uptake (and store) nutrients at the latter part of the season may influence growth of the vegetative tissues for the following season. The storage of nutrients within the vine tissues had been demonstrated to increase through increased irrigation (Sipiora, 2004; Klein *et al*, 2000). It is therefore proposed that the greater root growth within the surface horizons of profile M2 has allowed greater uptake nutrients through rainfall events after harvest (August), increasing the stored nutrients in these vines. This could explain why this profile had similar vine vigour while having a restricted root system and lower soil fertility.

Implications for vineyard management

Investigations at this site demonstrated that diverse soil properties can exist within close proximity in Tasmanian vineyards. Understanding the spatial variability of these soils is critical for their management as well as for vineyard production, which has already been suggested through other studies (e.g. Bramley and Janik, 2005). To assess the impact of soil type on vine growth it is important not only to understand the variations in soil type across the vineyard, but also to comprehend how the different soil attributes influence the availability of nutrients and soil moisture throughout the season. Observation of the entire profile is needed to gain this understanding. Without deep observation (> 1 m), the cause behind the excess vigour at M4 would not be fully understood, nor would the control of vigour at the highly fertile M1 profile have been revealed.

Of all the factors observed within these soils, management of soil moisture was assumed to be the most critical. However as soil moisture was inferred rather than measured during this study, future research is required to confirm this conclusion. At the bottom of the slope (M4) vines are overly vigorous from access to moisture available at depth where moist alluvial layers were observed (water table). Therefore regular irrigation of these vines will be unnecessary. Even with reduced irrigation, the supply of moisture from the lower soil horizons may still provide excessive vigour to these vines due to subsurface lateral flowing water in this low landscape position. This will be particularly prevalent during wetter years. The vertic soils on the upper slope also needs to have periods of profile drying to allow the natural wetting and drying cycles to continue. The dry periods are seen as necessary to reduce the root efficiency and restrict nutrient uptake from these fertile soils. If these soils were allowed to remain with a high soil moisture content (through increased irrigation or natural rainfall) then increased vine growth and potentially lower fruit yields will occur.

In contrast both M2 and M3 profiles will be prone to droughtiness due to restricted root growth throughout the subsoil. This will be more apparent at profile M2 where the high root numbers occur close to the soil surface.

Conclusions

The soils studied within this catena re-enforce the soil:root distribution relationships discussed within previous chapters. Fine roots (< 1 mm) were the most abundant root size and the majority of root growth occurred in the upper horizons (within 10 – 35 cm) despite the upper topsoil (0 – 10 cm) generally having the highest fertility. This was consistent with the recorded root distribution within all profiles discussed in previous chapters. Similar to previous chapters, the reduced root growth near to the surface was assumed to result from increased soil temperature and decreased soil moisture due to increased evaporation. The noticeable exception to this pattern of root distribution was at profile M2 which had the highest root growth at 0 – 10 cm depth. This was the only profile to display such a distribution of root growth throughout the entire study (all chapters) and the root distribution pattern at this profile was concluded to be due to higher surface soil moisture. At the bottom end of the catena, profile M4 also had increased root growth due to soil moisture, however in this case it was due to access to subsoil moisture (below 1 m).

Increased root activity at depth often corresponded to an increase in exchangeable cations, particularly exchangeable K^+ and exchangeable Ca^{2+}. The accumulation of these cations within the lower part of the soil profile demonstrates the limit of water movement through the profile and suggests water flow is impeded below this depth. Therefore it is likely that roots at these depths not only have access to increased nutrients, but potentially have access to higher soil moisture also. Further research is required to determine whether the cause of the increased root activity is due to either the increase in cations or soil moisture.

Total root numbers did not relate to above ground vine growth with low total root numbers supporting both low and high vigour vines (profiles M3 and M4 respectively) and moderate-high total root numbers supporting only moderate vigour (M1). This indicates that the efficiency of root system is more important than the number of roots per se. Root efficiency decreased through hostile soil properties such as coarse structure associated with high soil strength or high soil ESP, whereas root efficiency increased in areas of higher soil moisture. It is postulated that the efficiency of the root system can also change throughout the season. For example, in vertic profiles the expansion of cracks as the soil profile dries will restrict the volume of soil available for root growth. Therefore soils that have high fertility and high total root number may only result in moderate vine vigour (such as observed at profile M1). However, these soils have potential to produce highly vigorous vines if the climate becomes wetter and the soil does not dry out. It is anticipated that this change could be rapid (within one season) as the current root system is already large (e.g. one wet season will likely cause excess vigour). This chapter highlights the importance of soil moisture management for viticultural production.

8. General Discussion

General grapevine root distribution

The distribution and abundance of grapevine roots showed many similarities within the range of profiles studied. While the total number of roots differed, the percentage distribution of roots vertically through the soil profiles was very similar regardless of soil type. The highest root abundance occurred at 10 – 30 cm depth for all of but one of the 15 studied soil profiles. Root numbers then declined with depth below 30 cm with most profiles having 80 % of total root growth within a depth of 0 – 60 cm. This was shallower than reported by Smart *et al* (2006) who, after an extensive review of over 200 trench wall profiles (similar method to the present study), concluded that 80 % of root growth occurred at depths less than 1 m. In his review approximately 63 % of grapevine roots occur in the upper 60 cm. Most of the studies included in Smart's review were from either North America or South Africa in which the effective rooting depth may be deeper than the soils observed in the present study. Regardless, both the present study and at that undertaken by Smart *et al* (2006) demonstrate that the majority of grapevine root growth occurs in the upper portion of the profile (generally < 60 cm), with declining root numbers below 100 cm. Decreased root number with depth was correlated with increased in clay content, increased in soil penetration resistance and a decrease in soil fertility and organic matter (and hence biological activity) with depth. However, there were notable exceptions to this generalisation which will be discussed in detail later in the chapter.

Limited root growth was also observed in the upper 0 – 10 cm in all but one of the soil profiles, with many soil profiles having no roots recorded within 0 – 5 cm. This was despite these layers having the highest soil fertility and lowest soil penetration resistance. Similar lack of surface roots has been noted in previous studies of grapevine root distribution, however most previous studies describe the reduction in roots within the upper 0 – 20 cm or 0 – 30 cm of the soil profile rather than within the 0 – 10 measured within the present study (Saayman and Van Huyssteen, 1983; Soyer *et al,* 1984; Dowley *et al*, 2002; Morlat and Jacquet, 2003). The cause of the limited root growth observed in these studies was associated with either intensive cultivation of the vine row or through competition from the root system of cover crops or weeds. Some authors suggest that the lack of near surface roots could also be an evolutionary trait of grapevines that developed through intensive competition with other plant species (Morano, 1995 cited in Smart *et al* 2006; Smart *et al* 2005). As the examined soil trenches in the present study were orientated parallel to the row, the upper 10 cm also corresponded to soil contained within the mound of most profiles. The surface of the mounds was kept free from vegetation through either mechanical cultivation or herbicide application, which is thought to have resulted in higher surface soil temperatures and greater moisture evaporation (Lanyon *et al*, 2004; Myburgh and Moolman, 1993; van Huyssteen and Weber, 1980). It is therefore assumed that the reduced root growth in the near surface soil was in part due to limited moisture availability. The exception was profile M2 which had the highest root abundance within 0 – 10 cm, which was attributed to greater soil moisture. It is expected that if the surface condition of the other profiles were altered to increase the availability soil moisture (e.g. mulch application) then an increase in root growth within these regions would result.

While the vertical distribution of roots was similar between all profiles, the horizontal distribution of roots varied considerably between soil profiles. The horizontal root distribution was strongly dependent on soil structure and soil strength within all profiles and root growth was mainly contained to areas of weakness such as structural cracks, sand in-fill and/or old prior roots. This was more evident where the primary structural units were coarse to very coarse and had high internal ped strength which created fewer favourable rooting pathways. This was particularly the case within many subsoils and was often intensified by other constraints to root growth such as low soil pH, high ESP and/or shallow saline watertables. Therefore the extent of these favourable properties determined how widely the roots were distributed across the profile face. These properties will be individually discussed in more detail later in this chapter.

Fine roots (< 1 mm) were the dominant root size across all profiles. Reduction in root abundance occurred as root diameter increased, with coarse roots (> 5 mm) normally accounting for less than 1 % of the total root number. The abundance of the fine roots was consistent with other studies of root distribution (Van Huyssteen, 1988; Dowley *et al* 2002; Smart *et al* 2006).

Influence of soil properties on root growth, vine vigour and vine yield

While consistent relationships were observed between soil properties and root distribution, there was no clear relationship between vine growth and the size of the root system. Most importantly, a large root system did not always produce high vine growth and a small root system did not always result in low vine growth. This clearly signifies that the efficiency and function of the roots is more important than total root abundance. Root function has previously been shown to be important for both nutrient and water uptake (Richards, 1983; Cass, 2004) and this is primarily controlled by soil properties. Therefore soils that have differing properties will also have a different 'optimum' root distributions for vine growth. Consequently soil properties need to be considered in order to understand the influence of root distribution on vine performance.

The key therefore is to understand how the relationship between soil function not only influences root growth, but also how it influences the uptake of water and nutrients.

Soil depth

Soil profiles that had restricted soil depth and hard substrates also had limited root distribution. Vines growing at the shallow soils also had significantly lower pruning weights as well as significantly lighter bunch weight and lower fruit yields. This indicates that in shallow soils, reduced vine growth is related to reduced root growth despite unlimited irrigation applications during the growing season. This is similar with the findings of Van Huyssteen (1983) who demonstrated decreasing vine health with decreasing soil thickness. Changes in soil thickness were found due to either natural variation or due to soil modification through site clearing and vineyard establishment. In Chapter 5, the difference in soil depth was due to variation of soil thickness over bedrock, whereas in Chapter 4, it was through increasing topsoil thickness by the scalping and removal of topsoil from one area and placing it at another. In both cases the profiles with reduced soil depth (M7 and Kurosol-Unburnt respectively) had less abundant root development and significantly lower pruning weight and yield than the comparison profiles.

Given the similar soil chemistry for all the profiles profiles compared at the basalt transect (Chapter 5), the reduced soil volume at profile M7 indicated the shallow soil depth resulted in lower nutrient availability. This was exacerbated by increased stone content that was also present within the subsoil, further decreasing the soil fine earth volume within M7. Along with reduced access to soil nutrients, the reduced soil volume available also meant that there was a reduced capacity for the soil to retain and supply moisture when needed. While the underlying bedrock was highly fractured with potential for cracks to allow root growth, it had high permeability but low moisture holding capacity. As a result it is likely that any water that infiltrated to this porous bedrock layer would be quickly transported away from the rootzone both vertically and laterally. This is supported by anecdotal evidence that excessive irrigation a the site regularly resulted in seepage of water lower in lower landscape positions on this soil-rock type combination (C. Surios, pers comms – vineyard manager)

The reduction in topsoil thickness at the Kurosol-Unburnt profile (Chapter 4) not only reduced the moisture holding capacity of this profile, but it also resulted in a corresponding reduction in soil fertility. Consequently the roots within this profile not only had less soil volume to explore, but they also had fewer nutrients for vine growth (when compared to the higher fertility and thicker topsoil of the Kurosol-Burnt profile).

Therefore both profiles with reduced soil thickness had less stored nutrients (through decreased soil volume) which was compounded by lower soil moisture availability to transport nutrients to the roots. Vines grown on shallow soils have previously been shown to have low vine water and nitrogen status which leads to early shoot growth cessation and lower yield (Coipel *et al*, 2000). While moisture status or nitrogen contents were not measured during the present study, it is speculated that this was the major cause of the reduced cane weight and lower yield at both the Kurosol-Unburnt and M7 profiles.

Deep soil layers were also associated with increased vine vigour in some profiles. This was particularly demonstrated at profile M4 (Chapter 7) where increased root growth occurred below depths of 110 cm within buried soil horizons with clear seepage from a proximal groundwater level. The excessive vigour of these vines was due to the increased root growth and obvious higher moisture availability of these deeper horizons. However, increased soil depth did not always produce higher vigour. Within Chapter 6, the deepest profile (FM1) had lower vigour than the shallower FM2 and FM2b profiles. This was assumed to be due to different moisture availabilities of the respective profiles due to differences in landscape position and suggests that water retention in individual soil layers is more important than depth *per se.* Further long-term seasonal studies of how these profiles store and release moisture would help to confirm this.

Soil structure and soil strength

Soil structure had a primary influence on root growth. Roots consistently grew between the structural units of the soil at all profiles, regardless of the soil type or the type of structure. This was particularly evident in horizons where the structural units were coarse which resulted in root growth being confined to distinct regions. This became apparent on the images of root distribution when the width of the structural unit was coarser than 50 mm as this was larger than the resolution of the imposed measurement grid. While the influence of soil structure on root growth was very evident within subsoil horizons, it was also observed within the topsoils. Topsoil horizons had smaller structural units allowing greater distribution of the roots as there were more spaces between peds. Unlike subsoils, root growth within the topsoils was not restricted by soil strength as penetration resistance ranged from 0.5 – 1.5 MPa. This is lower than the suggested critical limit for vine root growth of 2 MPa (Myburgh *et al*, 1996, Van Huyssteen, 1983). This was one reason why higher root abundance was observed in the topsoil of every profile.

Within the subsoils, root growth was restricted by penetration resistance and many of the subsoils had soil penetration resistance values greater than 2 MPa in the soil matrix and peds. Within these soils, regions of lower penetration resistance corresponded to either the presence of structural cracks (e.g. profile FM1) or sand-filled cracks (e.g. profiles Kurosol-Burnt and Kurosol-Unburnt). These regions also had greater concentrations of roots. The difference in subsoil root distribution therefore occurred due to the size and degree of development of the structural units. Soils with coarsely structured subsoils had restricted rooting conditions in which much of the profile was not available for root growth punctuated by distinct regions of densely populated root growth. In contrast, soils with finer subsoil structure allowed more diverse root distribution and access to more of the soil profile. This point highlights the limited soil volume, in particular in subsoils, which is actually utilised by the vine. Studies by Hardie (2011) also suggest these same cracks are the primary pathways for water infiltration into texture-contrast soils. The correlations between the root size classes were also strong where the coarse structure had measured penetration resistance close to and greater than 2 MPa. These correlations support the observation of restricted root conditions by indicating that roots of different sizes were more likely to be growing together. This also supports the notation that 2 MPa is a critical limit for vine root growth.

Correlations between roots of different size were also strong within soils with high ESP, such as profiles M2 and M3 where limited root growth was associated with ESP values greater than 15 %. While penetration resistance was not measured at these profiles, dispersive soils with high ESP such as these are known to have high soil strength (Robinson, 2005) and it was assumed that this was the cause of the vine roots being constrained within sandy cracks. Both Khanduja *et al* (1980) and Samra (1986) demonstrated a reduction in cane growth due to high soil ESP, however no cause for the reduction was provided other than increased ESP. In the present study, while soils with high ESP had restricted root growth there was no clear relationship between high ESP and vine growth. This was partly due to differing levels of dispersion and corresponding soil structure between the profiles and potentially through the mitigation of restricted moisture availability through irrigation. It may also be due to lower ESP values than the studies by Samra (1986) and Khanduja *et al* (1980) who measured vine response up to an ESP of 67% and 75 % respectively.

Within the Kurosols, restrictions to root growth not only occurred through the coarse soil structure with high MPa and/or high ESP, but root growth was also inhibited by the low pH of the subsoil and correspondingly high values of exchangeable Al^{3+}. This demonstrates that there are often many interacting causes of root restriction within the soil profile. The influence of low soil pH will be discussed in more detail within the 'Soil nutrition' section of the chapter.

Constrained root growth was also observed in soils with vertic soil structure (profiles M1, FM1, FM2B and FM4) in which the bulk of the root growth was constrained to cracks within all profiles. However differences in root distribution were observed between the vertic profiles depending on the size of the structural units. Root growth was more diverse where the soil structure was finer (e.g. M1 and FM1) whereas profiles with coarser structure had more constrained root growth (e.g. FM4). As previously mentioned, the cracks between peds allowed increased root growth as they corresponded to areas of lower penetration resistance. However as the soil dries, the penetration resistance increases (Cass, 2004). As these soils are vertic and prone to cracking, the crack faces will preferentially dry more than the soil matrix and therefore have a higher penetration resistance than the bulk soil. Consequently it is speculated that as the profile dries the roots become increasingly confined within the cracks and are less able to access the moisture stored within the soil peds or aggregates. As cracks continue to expand as the profile dries, there will also be less contact between the roots and the soil and perhaps also root breakage. This will reduce the efficiency of these roots and further reduce uptake of moisture and nutrients from that part of the soil profile. This is best shown by M1 which while it have very high root counts this was not matched by an equally high fruit of cane weight; and this was a very reactive cracking clay soil.

Regardless of the method of root restriction (coarse soil structure, high MPa, high ESP or low soil pH), the consequence of reduced root access to the soil within the soil profile was similar. While soils with a coarse soil structure had greater observed root restriction than soils with finer structure, it is concluded that this only translated into reduction in vine growth where access to moisture and stored nutrients was also more limited.

Structural cracks were likely to be zones of preferential water movement through the profile, particularly when the soils are drier (Hardie, 2011). This can result in non-uniform wetting within the soil profile and storage of soil water at depth within cracks and voids rather than the surrounding soil matrix. Increase moisture status of soils with shrinkage cracks and sand infills was suggested by higher levels of exchangeable cations occurring in soil layers corresponding to the depth of cracking (particularly K^+, Na^+ and Mg^{2+}) and grey subsoil colours in the vertosols. This suggests translocation of these cations from higher horizons through increased water movement. Within the vertic profiles, grey colours were also dominant within the lower subsoil, indicating the base of the cracks frequently have higher moisture contents. This was also generally associated with lenticular structure.

The preferential flow paths were also the preffered sites for root growth, presumably due to the combination of lower penetration resistance, increased soil moisture availability and higher nutrient status that occurred from translocation of nutrients from the topsoil. Conversely it was reasoned that when the supply of moisture to these regions is reduced the supply of moisture to the vine is also greatly reduced, as the roots have limited access to moisture contained within the soil peds and coarse structural units. The observation of root growth at profile M3 (Chapter 7) suggests how important these processes are. It appears that the increased root growth at the base of the structural cracks at M3 allowed greater capture of water moving preferentially through this profile and allowed vines to have similar growth to other profiles (e.g. M1 and M2) but with substantially lower root numbers. Similar increased root growth was also observed at the base of structural cracks of many of the vertic profiles (e.g. M1, FM1 and FM2b) indicating that preferential uptake of moisture is also potentially occurring at depth from these profiles. However, the occurrence of this moisture uptake did not have an influence on vine growth even though these profiles were expected to have higher moisture holding capacity. Instead it appears that the development of cracks in these profiles reduced root efficiency in the upper portion of the profile as the soil dried. Drying of the profile was more pronounced later in the season due to reduced irrigation and infrequent rainfall. Thus the drying of the profile as the season progressed resulted in reduced vine vigour due to a smaller proportion of roots participating in water and nutrient uptake; in part due to root breakage and physical separation from the soil as it shrinks. This may explain why the higher root numbers of vertic soils did not produce more vigorous vines than other soils. Access to this moisture deep within the profile may also be the cause of the higher yield observed on these soils. Therefore not only does the amount of soil available for root exploration decreases as the soil dries out, the method of water infiltration into the soil also changes as shown by Hardie (2011).

Many authors suggest that highest quality grapes occur through either moderate availability of moisture or mild water deficits (Matthews and Anderson, 1988; Seguin, 1986; Gladstone, 1992; Koundouras *et al*, 1999). It is therefore likely that the reduction in moisture availability achieved through the cracking of the vertic soils may have also influencing wine quality. This needs to be confirmed through future research.

Along with differences in water entry into the surface of the soil profile, soil structure and pore distribution also influences the water movement within the soil. Well-structured soils with many pore spaces also allow increased drainage and water distribution within the profile. The well-structured Dermosol soil profile (Chapter 4) demonstrated this by having a lower water table than the coarsely structured Kurosol-Sodic profile, even though the Dermosol was in a lower landscape position.

Soil Nutrition

No clear relationships were observed between soil fertility and vine growth. While low pruning weights and yield were associated with low fertility at some profiles (e.g. Kurosol-Unburnt and Kurosol-Sodic), lower fertility of other profiles did not produce reduced vine growth (e.g. M2). This could partly be through the influence of other soil constraints such as reduced soil thickness and/or shallow water tables. This suggests that the role of soil nutrients is only one (and often minor) component of producing vine growth and yield and the access and supply of nutrients is also important. The overall vineyard management may also have masked some of these differences, particularly through activities such as irrigation and fertilisation.

Undertaking multivariate analysis across the measured soil properties was one approach that was considered to unravel some of this complexity. However this was tested and then rejected as it was felt that the sample size was not sufficient to encompass a normal distribution of the factors. Also the soil samples collected for analysis were from along the vine row whereas vines can potentially also access nutrients from the inter-row, meaning the nutrition of the analysed soil may not entirely relate to the measured vine growth. White (2011) proposed that the nutrition of the inter-row is one area that needs to be considered when attempting to identify benchmark soil fertility values. Other authors have indicated that multivariate studies can often produce nonsensical results and do not explain the mechanisms involved (Moran, 2001; White, 2009). Despite this, it is still possible to make some comments on the measured soil chemical properties on root distribution and vine growth from the measured dataset and these are provided below.

Soil pH

The Kurosols were the only soils studied with strongly acid subsoils (pHw < 5.5) and associated high levels of exchangeable Al^{3+}. As discussed in Chapter 4, the low pH hindered root growth within these horizons and roots were restricted to either sandy cracks or to within old prior roots in which pH was higher. Once within these restricted areas roots were still able to penetrate deeply within the subsoil. Root growth within sandy cracks was observed at depths greater than 120 cm at the Kurosol-Burnt profile despite this subsoil having the lowest pH and highest exchangeable Al^{3+}. This suggests that the measured exchangeable Al^{3+} (> 150 mg/kg) was either not an impediment to root growth or that the conditions within the sandy cracks (and prior old roots) were more favourable to root growth than indicated by bulk soil chemistry. While it was assumed that the roots within the Kurosols were restricted by the low pH, these soils also had high penetration resistance, high ESP and/or shallow saline water tables that may have also contributed to the measured root distribution. Nevertheless, the low pH and high exchangeable Al^{3+} were considered an impediment to root growth. Measurements of vine nutrition demonstrated that low soil pH was associated with lower leaf phosphorous and higher leaf manganese and iron indicating that acidic soil conditions affected uptake of other nutrients.

The remaining soil profiles studied all had soil pHw in a range of 5.5 – 8.5 which were considered to be within the recommended range for grapevine growth (Cass, 1998; Lanyon *et al*, 2004)

Electrical conductivity

Many of the profiles showed increased electrical conductivity (EC) values with depth with subsoil EC values ranging from 0.2 – 0.8 dS/m. While this was within the range where own rooted vines begin to be affected (Cass, 1998; White, 2003), no discernible differences were recorded. In several profiles increased root growth was associated with increased EC values (e.g. M1, M3, M4, FM1, FM2b) however this was more likely due to expected increases in soil moisture rather than the increased EC *per se*. The only profile to demonstrate reduced vine growth associated with increased EC was Kurosol-Sodic in which high EC was resulted from a shallow saline watertable such that the effect of the EC and drainage were confounded.

Exchangeable cations

Although differences in exchangeable cations were observed between the soil profiles, no clear relationship with vine growth was evident. This absence of a relationship was unexpected and remains largely unexplained. It may be through values of exchangeable cations generally being quite high or possibly through the roots accessing nutrients from other parts of the soil that were not analysed (e.g. from soil within the inter-row). However a number of observations were made from the measured analysis. From profile M2, it seems likely that exchangeable Ca^{2+} values of 9 cmol(+)/kg are non-limiting to vine growth as this profile had similar pruning weights to profiles with much higher exchangeable Ca^{2+}. In some profiles there was an association between increased root growth at depth with increased exchangeable K^{+} (e.g. profiles M1, M3 and FM1). However, these depths also had elevated exchangeable Na^{+} and increased EC values suggesting the increased root growth may also have resulted from increased soil moisture availability. Horizons with a high exchangeable sodium percentage (ESP) also had decreased root growth. This was assumed to be an indirect effect caused by the effect of sodium content on soil structural conditions rather than an imbalance of cations. In fact many profiles had increased root growth associated with high exchangeable Na^{+} values (e.g. M1, M3 and M4) indicating that exchangeable Na^{+} values of less than 3.6 cmol(+)/kg are non-inhibiting to root growth. High vine vigour was also associated with profile M4 suggesting this ESP value also does not decrease vine growth.

Comments about future soil studies

It is clear from the current study that more work is needed to determine benchmark soil values for optimum vine growth. Any future work needs to also take into account the moisture storage and flux of the profile as this is most likely to influence nutrient storage and uptake throughout the season. Even though the majority of the roots were in the upper 60 cm, excavation of the whole soil profile revealed vine roots have a number of mechanisms for overcoming subsoil constraints that were not apparent at shallow depths. Prediction of vine growth and performance prior to vine establishment therefore requires excavation and analysis of the entire soil profile.

For ongoing soil monitoring of nutrients within the vineyard, analysis of 10 – 30 cm depth may have some merit due to the highest root growth of all profiles corresponding to these depths. The general lack of significant root growth in the upper 0 – 10 cm indicates that monitoring of only this depth is not really appropriate for accurate assessing the nutrition status of vineyard soils.

Determining soil and vine variation in the landscape

The studied soils showed that variation in vine growth and yield was related to variations in soil properties and their effect on root efficiency and function. Therefore understanding variability of soil in the landscape is important for appropriate management of the variability in vineyard production. In this study, the available geology and soil maps gave an indication of what soil type might be there, but they did not contain the level of detail about variation in soil properties that will influence vine growth at a local field scale. This is particularly the case with the high level of colluvial land or re-working of the soil observed within the Tasmanian landscape. Many of the observed soils within the present study had influences from parent materials unrelated to the underlying lithology. The evidence of stone-lines in many profiles indicate that slope processes such as soil creep, slope wash and other forms of mass movement (e.g. earth or debris flow) have influence the distribution of soil in the landscape. Even when the soils were highly related to the underlying bedrock, they still showed evidence of reworking which has influenced their properties and thickness. It is suggested that for Tasmanian soils observation to at least 1.5 metres (unless inhibited by bedrock) is required in order to understand water movement at depth. This is particularly important on slopes where colluvial processes dominate soil formation especially where there are changes in underlying lithology.

The use of remote sensing such as EM38 for determining soil variability is one step to understanding these factors (Bramley, 2001, 2003, 2004). However this study has shown that when using EM38 evaluation, both horizontal and vertical dipoles are important to determine the overall impact on vine productivity. For example in Chapter 7, if only the horizontal dipole was used, then the highly vigorous soils (profile M4) would not have been delineated from those with lower vigour. Conversely, if only the vertical dipole was used, then other parts would have been delineated as lower vigour when in fact they had access to moisture higher in the profile (e.g. M2). This also re-enforces the need to calibrate ECa to soil properties. It is suggested that for Tasmanian soils observation to at least 1.5 metres is required (unless inhibited by bedrock) in order to understand water movement at depth. This is particularly important on slopes where colluvial processes dominate soil formation especially where there are changes in underlying lithology.

The use of infrared imagery to determine plant cell density (PCD) generally showed a good relationship with the on ground pruning weights. This demonstrates that PCD technology can assist with determination of variability in vine growth within the vineyard. This supports previous work on use of remote sensing of vineyard variability (Dobrowski *et al*, 2003; Johnson *et al*, 2003; Bramley, 2003, 2005; Bramley and Hamilton, 2004; Wells, 2011). However differences in PCD did not always reflect different soil types. There were also situations where the PCD values indicated similarities in vine growth however significant differences in pruning weights existed. This occurred at both low PCD values (e.g. comparing profiles FM1 and FM4 discussed in Chapter 6) as well as high PCD values (e.g. comparing profile M4 with M1 and M3 discussed in Chapter 7). This was potentially due to PCD values being derived on leaf density whereas the pruning weights were due to measurement of woody growth. While differences in vine vigour were measured between the profiles, all of the vines had average cane weights indicating moderate to high vigour (Smart and Robinson, 1991). The high average cane weight recorded within these vineyards may indicate that a greater leaf area is required due to the cool climate (Kliewer and Dokoozlian, 2005). This may also have saturated the indices used in measuring PCD, causing similar values to be recorded (Johnson *et al*, 2003).

One limitation of using remotely sensed PCD to determine vineyard variation is that the variation can only be determined once the investment of establishing a vineyard has been made. This makes it a good tool for assessing variability in current vineyards, but not particularly useful for assessing the variability of potential vineyards. While both types of remote sensing helped show variation in the landscape, examination of the soil profile is still required to understand the causes of the variation. These causes need to be understood before any changes in management are undertaken as there may be different causal factors arising from different soil properties.

Management of soil variation within the vineyard

In vineyard blocks that contain multiple soil types the management requirements of the different soils may influence other parts of the vineyard, for example more frequent irrigation of shallow profiles could potentially increase the availability of water in lower landscape positions. Different soils have different management requirements for vine growth, creating different management zones within the vineyard. Management of soil in one part of the landscape can affect the soil attributes in another part of the landscape. This was apparent in the basalt transect where irrigation of the shallow M7 profile has potentially increased water availability within the soils on the side-slopes (particularly profile M9). The ability to identify these variations before vineyard establishment enables blocks to be structured with appropriate infrastructure to accommodate this variation. Where this is not possible or where vineyards have already been established, alterations to the infrastructure (such as additional or reduced irrigation lines) may provide tools to minimise the amount of variation.

9. Conclusion

Root distribution varied considerably across the studied sites, with no clear relationship between the size of the root system and the amount of above ground vine growth. While it was notable that vines with low vigour generally had small root systems, vines with small root systems did not always produce vines with low vigour. Conversely, vines with abundant roots did not always have the most abundant above ground growth. This suggests that access to soil moisture and nutrients has greater control over above ground growth than simply the size of the root system. Consequently it is proposed that vine growth is more closely related to root efficiency and function rather than root volume *per se*. Further study is required to determine the relative contribution of root efficiency as opposed to function on vine vigour.

While there were no clear relationships between the size of the root system and the amount of above ground growth, there were clear relationships between soil properties on both root and above ground growth. Where soil properties were more restrictive, greater root growth was required to produce vines of similar vigour. For example, vertic soils had high number of roots but only moderate vine vigour, however in soils where soil moisture was readily available (e.g. through an accessible watertable) the additional soil moisture meant that high vine vigour could be supported with few numbers of roots.

This study confirmed that one of the principal restrictions to root volume was mechanical impedance. Soils with penetration resistance values greater than 2MPa showed greatest restriction to root growth. This supports existing values in the literature which suggest vine root growth is reduced in soils when penetration resistance is greater than 2 MPa. In this study, excessive penetration resistance resulted from a variety of materials including coarsely structured subsoils, underlying bedrock and highly reactive vertic clays.

Root growth was also observed to be restricted chemically through low pH ($pH_w < 4.8$) as well as in soils with high ESP (> 15 %). Where high ESP values occurred, it was unclear whether the restriction was due to high sodium levels or due to mechanical impedance associated with clay dispersion and hardsetting. It was reasoned that the high mechanical impedance of these soils was also associated with restricted root growth, however chemical restriction through high sodium levels could not be ruled out.

In soils where both chemical restrictions occur and mechanical impedance coexist, soil amelioration needs to overcome both the chemical and physical constraints for root growth to occur. For example, amelioration of Kurosols to improve root growth requires both increased pH as well as decreased soil strength, as measured by penetration resistance. Current management of these soils usually involves ripping to reduce subsoil penetration resistance, however low soil pH conditions remain unchanged during this action. Further research is required to trial the use of lime slotting during ripping or similar technology to address both the chemical and physical constraints to root growth. In Tasmania, Sodosols and many Kurosols also have sodic subsoils and using lime-filled slotting will also stabilise against dispersion.

This study highlights some key areas to address when determining benchmark soil test values for optimum vine growth. The observed lack of root growth in the upper 0 – 10 cm of most soil profiles indicates that monitoring of only this depth is inappropriate for assessing the nutritional status of vineyard soils. Highest root growth generally occurred within 10 – 30 cm of the soil surface implying that analysis of this depth maybe suitable for ongoing nutritional monitoring. Any research involving determination of benchmark soil test values need to also need to take moisture availability into consideration. Further research is required to confirm the flux of water and nutrients within the soil profiles and quantify these relationships to grapevine growth.

Sensory assessment of batch made wines undertaken by Wells (2011) demonstrated that where access to soil moisture was non-limiting, increased vine vigour reduced fruitfulness and influenced wine attributes, without influencing wine score. For example, in Pinot Noir, increased access to soil moisture resulted in wine with more herbaceous and earthy flavours compared to more vegetal and red fruit characteristics from sites with water limited vines. These differences were related to increased shading and decreased airflow through the canopy associated with increased vine vigour (Wells 2011).

Understanding the variability of soil properties within the landscape is important for appropriate management. Monitoring of soil moisture needs to account for how the different soil profiles store and releases moisture. This varies dependant on soil properties and means that a blanket approach to management cannot be taken across the viticultural industry as different depths may need to be monitored depending on soil type. This is especially important within soils with vertic properties where monitoring at the base of cracks will also be required as well as within the upper profile. Similarly, where vines can access deep sources of water (e.g. a water table) then these depths need to be accounted for within the water budgeting.

This study has demonstrated that continued expansion of the Tasmanian viticultural industry is not dependent on the continued identification of locations containing a specific soil type or soil-geological association. Rather, this study demonstrates that suitable conditions for vine growth exist for a range of soil types, in which soil depth, chemical and physical properties enable adequate root development to meet vine requirements for water and nutrients. Furthermore this study has demonstrated that in soils which do contain restrictive soil properties, the vines employ a range of strategies to avoid or at least partly overcome these restrictions.

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